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AFML-TR-74-65
Part II

THE EFFECT OF TEMPERATURE AND STRAIN RATE ON THE TENSILE PROPERTIES OF KEVLAR AND PBI YARNS

TECHNICAL REPORT AFML–TR–74–65, PART II

MAY 1974

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This report was prepared by Fabric Research Laboratories, Dedham, Mass. under U. S. Government Contract No. F33615-73-C-5034. The work was initiated under Project 7320, "Fibrous Structural Materials," and was conducted from January 2, 1973 through January 31, 1974. It was administered under the direction of the Air Force Materials Laboratory, Air Force Systems Command, with Mr. Stanley Schulman acting as project engineer.

Mr. Norman J. Abbott was the FRL director responsible for the overall program. The low strain rate yarn tests were carried out by Mr. David S. Brookstein; the high strain rate tests by Mr. James G. Donovan; the testing of single fibers and twisted yarns by Mrs. Meredith M. Schoppee and Miss Pamela F. Aist; and the transverse compression studies by Dr. S. Leigh Phoenix and Mr. John Skelton. The authors wish to express their appreciation to Dr. Milton M. Platt for handling contractural matters and many helpful discussions throughout the course of the work.

This report was submitted by the authors in March 1974.

This technical report has been reviewed and is approved.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
The tensile properties of Kevlar 29 and Kevlar 49, PRD-49 IV and PBI yarns were measured at low (0.167%/sec) and high (8000%/sec) strain rates over the temperature range -65° to 800°F. The effect of twist on tensile properties was determined also for Kevlar 29 and 49 yarns, as well as the knot and loop strengths of these yarns at various levels. Single fiber properties were measured for Kevlar 29 and Kevlar 49, including tensile properties, the effect of bending, twisting and lateral compression. Critical velocity under lateral impact and dynamic modulus was also determined.

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SECTION I

INTRODUCTION AND SUMMARY

An important phase of the FRL development effort for the Air Force is to analyze and characterize new fibers as they become available, and particularly to study those having properties which may be of particular value to the Air Force. A major part of our work this past year has been devoted to a study of two particularly interesting new fibers. These are du Pont's Kevlar* 29 and Kevlar* 49. In addition, a third du Pont fiber called PRD-49 Type IV was included initially, but it was no longer available by about mid-year. Along with these three fibers, additional measurements were made of the properties of PBI yarn.

The tensile characteristics of all four of these yarns were measured at low and high strain rates (0.167% and 8000%/sec), and at temperatures of -65, 70, 200, 400, 600, and 800°F. Rupture tenacity and elongation, initial modulus, and rupture energy were determined. Critical velocity under lateral impact and dynamic modulus were also measured. The effect of yarn twist on tensile properties, loop and knot strength were evaluated, and throughout the values obtained were compared with published characteristics of nylon and Nomex yarn.

All of these measurements confirmed the fact that Kevlar fibers are of particular interest to the Air Force, and because of their extremely high tenacities offer the potential of significant weight saving in parachute and other materials applications.

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*Registered trademark of E. I. du Pont de Nemours and Co., Inc. for their aramid fiber.

SECTION II

THE EFFECT OF TEMPERATURE AND STRAIN RATE ON THE TENSILE PROPERTIES OF SEVERAL YARNS

1. Introduction

Previous Air Force programs have included extensive studies of the tensile properties of various yarns over a wide range of temperatures and strain rates. During the past year, the du Pont Company has increased the availability of Kevlar 29 and Kevlar 49 and interest in these unique, high-modulus materials has grown considerably. Therefore, early in May of 1973, a decision was made to embark upon a similar study of yarns made from Kevlar 29 (then designated Fiber B), Kevlar 49 (then designated PRD-49 III), and PRD-49 IV (which is no longer generally available). Since comprehensive tensile data had not yet been compiled for PBI yarn, it, too, was included in the program.

2. Testing Conditions and Techniques

Tensile testing conditions were selected after consideration was given to the unusual characteristics of the Kevlar series of yarns and to the need to compare results with similar data previously obtained for other materials, particularly nylon and Nomex. In earlier work strain rates of 1.67%/sec (100%/min) and 9000%/sec were used. However, the very low elongation to break of the Kevlar series (2 to 4%) necessitated compromise in the selection of strain rates. The Instron testing was limited to a strain rate of 0.167%/sec (10%/min) by the response time of the recorder. Reliable measurements of elongation required the use of a longer gauge length (~10 inches), which limited work at the higher strain rate to 8000 %/sec. Test temperatures of -65, 70, 200, 400, 600, and 800°F were initially chosen, based upon prior knowledge of the useful range of the four test materials. Relative humidity was maintained at 65% for tests at 70°F, following 24 hours of specimen exposure to these conditions. Tests at all other temperature levels were conducted after specimens were exposed at temperature for ten minutes.

The tensile characteristics of the Kevlar yarns made selection of an appropriate jaw system rather difficult. To adequately grip yarns of tenacities in the 20 gpd range with anything but capstan jaws seemed an unlikely prospect, but the accuracy of strain measurement with such grips is limited. And, since rupture strains being measured were generally 4% or less, it was necessary to minimize strain measurement error as much as possible. Toward this end, considerable effort was expended at the outset in an effort to develop an epoxy tab-flat jaw combination that would yield a clearly defined gauge distance and consequently, more accurate strain measurement. Although many epoxy systems were tried, none was found that was suitable at the higher temperature levels. Ultimately, the use of capstan jaws was unavoidable and the type illustrated in Figure 1 was used. The upper jaw-piece is a pulley around which the yarn passes in a 180° arc. The lower component

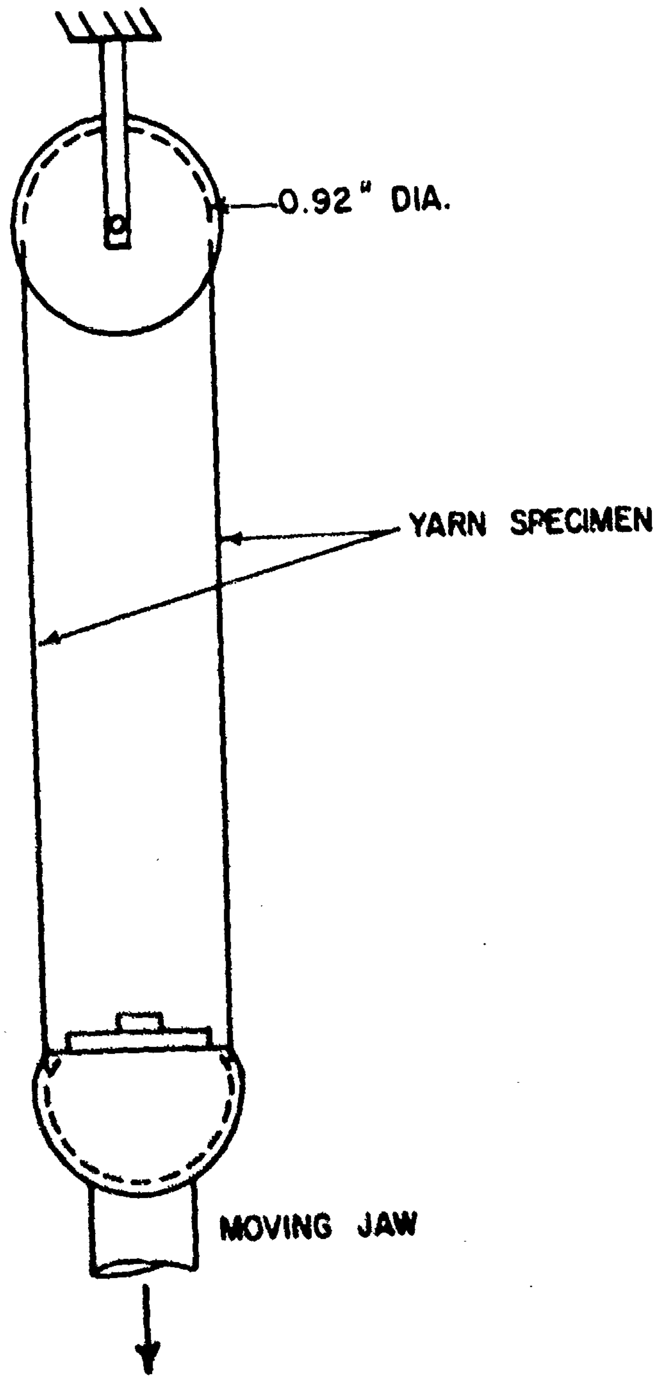

Figure 1. Tensile Test Configuration using Capstan Jaws

consists of a flat jaw, preceded by a semi-circular snubbing surface. Thus, two lengths of yarn are tested in parallel. Each length has 90° of wrap around the upper capstan and 180° of wrap around the lower. Since the strain distribution in the yarn is non-uniform at the capstan, the value of the true gauge length is not readily apparent and a method frequently described as "effective gauge length determination" was employed to compute a reliable set of gauge length corrections. This data was obtained by carrying out tensile tests at three different gauge lengths and plotting absolute extension vs nominal gauge length for several increments of load. These plots are presented as Figures 2, 3, and 4, and yield the following corrections, which equal the negative distance along the gauge length axis from "zero gauge length" to the zero load intercept: 0.8 inch for Kevlar 29, 0.4 for Kevlar 49 and PRD-49 IV, and 0.7 for PBI.

Three conditioning chambers were used to complete an extensive series of tensile tests. The FRL environmental test chamber can be mounted in an Instron tensile tester and was thus used for low strain rate testing over the temperature range of 200-800°F. This chamber could not readily be converted for use in FRL's high strain rate tensile tester at temperatures as high as 800°F, however. The most troublesome aspect was the need to accommodate a rigid, vibration-free, jaw system that could be moved into and out of the heated chamber for sample mounting. Another oven, originally incorporated into the design of a 1000-lb capacity high strain rate tensile tester built under Air Force Contract No. AF33(615)-2457 was available and was adapted for use in FRL's high strain rate yarn testing machine. This oven, by way of cutouts in the roof and floor and appropriate door hinge placement, can be rolled into place around a permanently fixed jaw system after the specimen has been mounted. For testing at -65°F, FRL constructed a two-chamber styrofoam enclosure that is adaptable to both Instron and high strain rate testing machines. One chamber of this unit is packed with dry ice, and the other chamber, connected to the first by two ports, is provided for the jaw system and specimen. A rheostat-controlled blower circulates cold air between the two chambers.

3. Interpretation of Results

Values obtained from room temperature tensile tests are usually expressed in terms of the original, unstressed fiber or yarn dimensions and weight. Rupture tenacity, for example, is commonly given as grams per denier based on the unstressed denier of the fiber or yarn, in spite of the fact that the actual denier at the time of rupture is less than this. Thus, the true tensile strength of the material is higher than that implied by the rupture tenacity figures. This is common textile practice, and is a convention used also for the calculation of a modulus or the normalized energy to rupture.

The problem becomes more complex, however, when tests are conducted at an elevated temperature. Exposure to high temperatures usually causes a fiber or yarn to shrink in length and, depending upon the conditions, possibly to change in weight due to loss of moisture and oxidation. One can define the initial denier, then, either as that at room temperature or as that at the elevated temperature at the start of the test. Tenacities which are calculated on

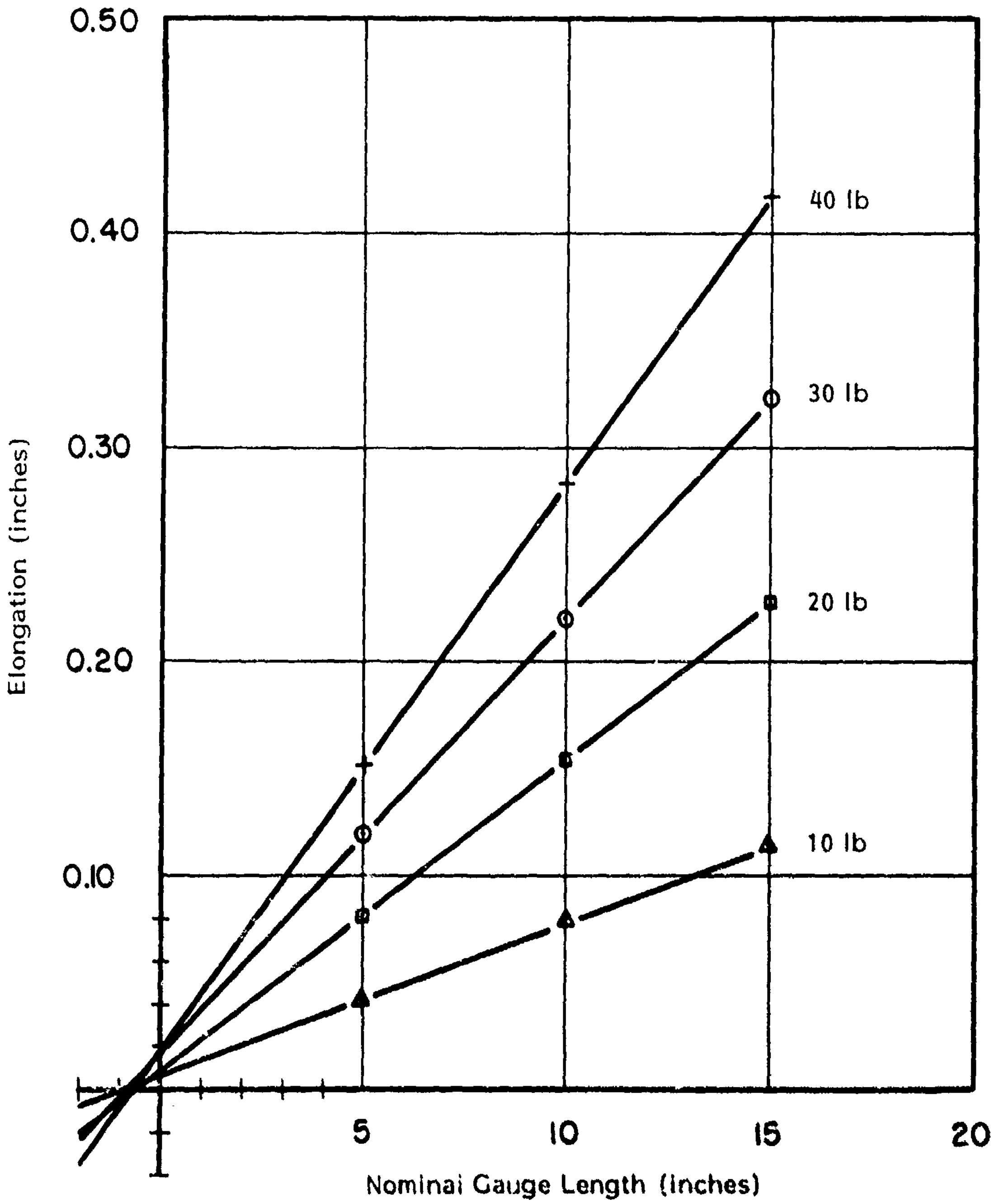

Figure 2. Gauge Length Correction for Kevlar 29 Yarn

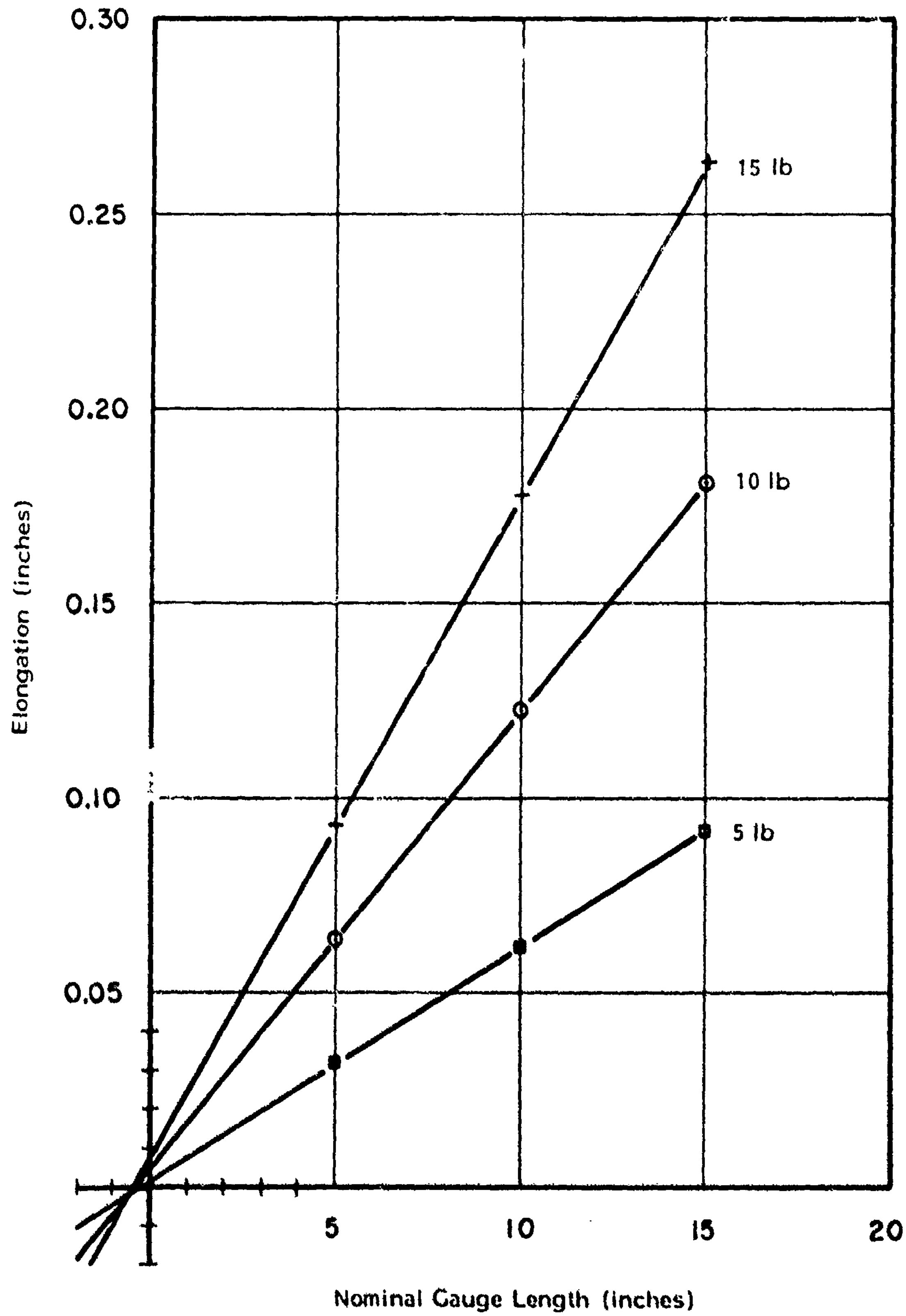

Figure 3. Gauge Length Correction for Kevlar 49 and PRD-49 IV Yarn

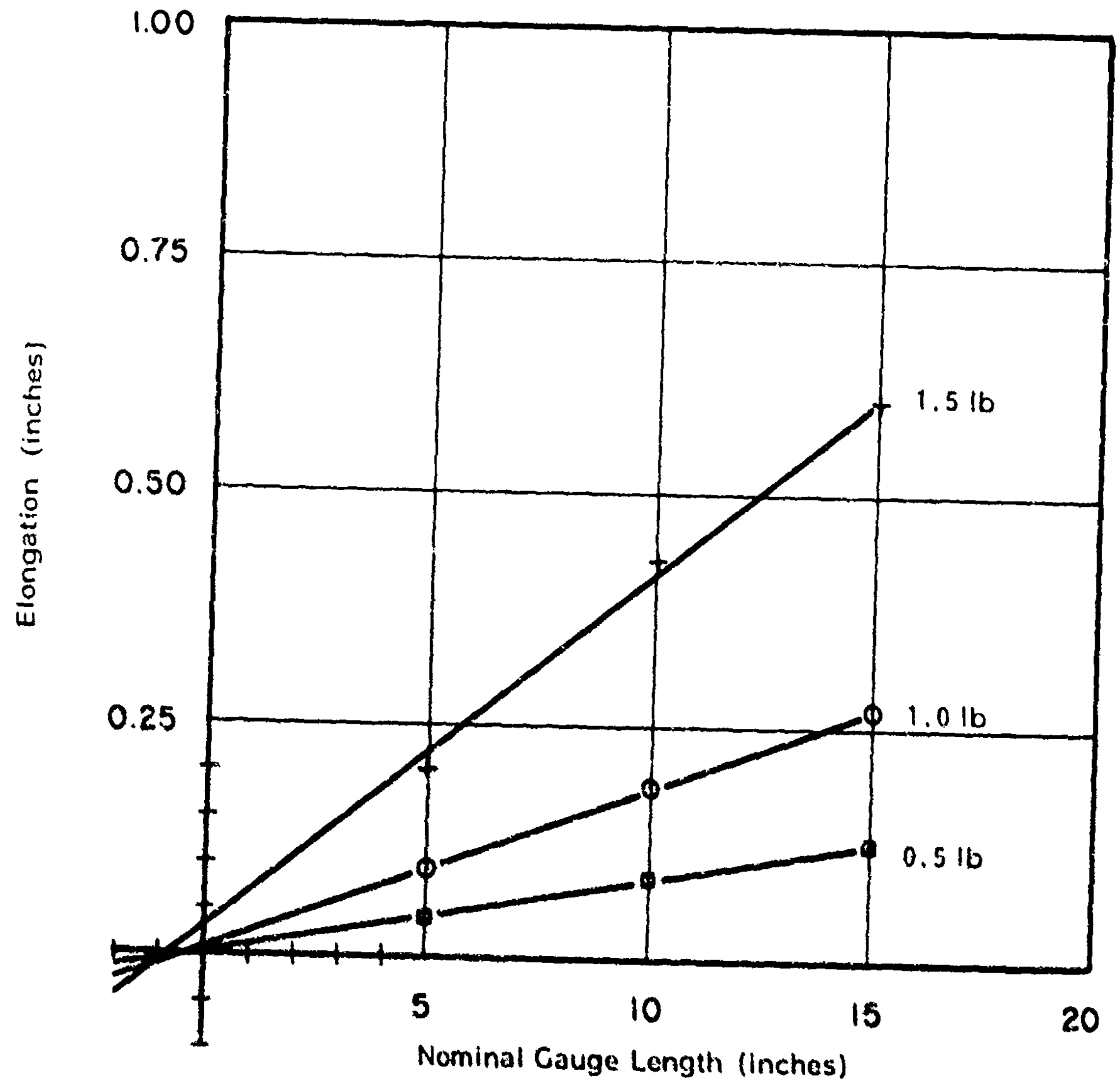

Figure 4. Gauge Length Correction for PBI Yarn

the basis of room temperature denier will reflect true strength changes, while those based on at-temperature denier will reflect tenacity changes in the normal sense of the term.

If tenacity were the only characteristic of interest, it would seem logical to use room temperature dimensions as a reference. Any quantities based on fiber length or length changes, however, such as elongation, modulus, and rupture energy present a different problem. Elongations based on room temperature length will result in values which will appear strange if the fiber shrinks at elevated temperatures. Thus, in elevated temperature tests, it will require some load to reach what will be defined as zero elongation, and the zero load elongation will be represented not by zero, but by a negative value which will represent the shrinkage. Values of modulus or rupture energy also become difficult to interpret accurately if they are based on room temperature rather than at-temperature dimensions.

There is no totally satisfactory solution to this dilemma. The most consistent way of expressing all of the measured quantities is to base them on at-temperature dimensions. This is what has been done in previous work at FRL (see report no. AFML-TR-70-267, Part II, for example). If values for shrinkage and denier change at each temperature are also given, all the information needed to translate the quantities to any other basis is available. Therefore, tenacity, elongation, modulus and energy values will be based upon at-temperature dimensions, with one exception. Tenacity data based upon room temperature denier is universally considered to be essential engineering information and so rupture tenacity will be reported in both ways. Table 1 is a tabulation of the rupture tenacities of all yarns tested under various conditions, based upon room temperature denier. Also included in Table 1 is similar data obtained by FRL under previous AF contracts (F33615-67-C-1731, F33615-69-C-1167) for nylon and Nomex. Figure 9, in a subsequent section, is convenient graphic presentation of rupture tenacity based upon room temperature denier vs test temperature. All other data reported herein will be based upon at-temperature dimensions and weight.

4. Measurement of Dimensional Changes at Test Temperatures

A series of yarn specimen exposures were made to determine weight change, length change, and the resultant denier change of each yarn type after ten minutes of conditioning at each test temperature level. The results of these exposures are presented in Table 2. Yarns of Kevlar 29, Kevlar 49, and PRD-49 IV showed no perceptible length change after exposure at each of the three lower test temperatues and only minimal shrinkage (1 to 2%) at the maximum temperature of 800°F. Thus, the denier changes measured for these materials are attributable solely to the removal of moisture or other volatile material. PBI yarn exhibited slight but measurable shrinkage at the lower temperatures, and at 750 and 800°F, it was reduced in length by 20% and 27%, respectively. Values of denier and gauge length used to calculate yarn properties at each temperature level are shown in the tabulations of individual test data in the Appendix, Tables 20 and 21.

TABLE 1

STRENGTH RETENTION OF YARNS AT VARIOUS TEMPERATURES

Material	Low Strain Rate (0.167%/sec) Temp (°F)	Rupture Tenacity[1] (gpd)	Strength Retention (%)	High Strain Rate (8000%/sec) Temp (°F)	Rupture Tenacity[1] (gpd)	Strength Retention (%)
Kevlar 29	- 65	22.9	110	- 65	18.0	103
(1500 den[5])	70	20.8	100	70	17.5	100
	200	18.3	88	170	17.4	99
	400	14.4	69	370	14.5	83
	600	7.5	36	570	9.9	57
	800	2.5	12	750	4.7	27
Kevlar 49	- 65	18.6	101	- 65	14.6	92
(400 den[5])	70	18.5	100	70	15.8	100
	200	15.3	83	170	14.9	94
	400	9.9	54	370	13.9	88
	600	5.8	31	570	12.9	82
	800	4.1	22	750	6.1	39
PRD-49 IV	- 65	21.5	114	- 65	15.4	92
(400 den[5])	70	18.8	100	70	16.7	100
	200	15.2	81	170	16.6	99
	400	10.0	53	370	12.2	73
	600	6.7	36	570	10.2	61
	800	4.8	26	750	5.9	35
PBI	- 65	6.3	117	- 65	7.3	116
(200 den[5])	70	5.4	100	70	6.3	100
	200	6.6	122	170	6.6	105
	400	5.5	102	370	5.2	83
	600	3.8	70	570	4.5	71
	800	1.0	19	750	1.8	29
Nylon[2,4]	-109	9.8	146	-109[3]	8.8	109
(1050 den[5])	70	6.7	100	70	8.9	100
	200	5.8	87	200	7.1	88
	400	3.4	51	400	4.2	52
Nomex[2,4]	-109	7.1	139	-109[3]	5.8	112
(1200 den[5])	70	5.1	100	70	5.2	100
	200	4.6	90	200	5.6	108
	400	3.3	65	400	4.2	81
	600	1.6	31	600	3.0	58

[1] Tenacity based on denier at 70°F.

[2] 1.67%/sec - low strain rate.

[3] 3000%/sec at -109°F.

[4] The nylon and Nomex curves at high strain rate passed through a stress maximum prior to rupture. The rupture tenacities given correspond to the point of maximum stress.

[5] Nominal denier at 70°F.

TABLE 2

WEIGHT CHANGE AND SHRINKAGE AT TEMPERATURES SELECTED FOR TENSILE TESTING

		Kevlar 29	Kevlar 49	PRD-49 IV	PBI
-65°F	Weight Change (%)	0	0	0	0
	Length Change (%)	0	0	0	0
	Denier Change (%)	0	0	0	0
200°F	Weight Change (%)	-3.8	-3.9	-4.1	-6.7
	Length Change (%)	0	0	0	-0.6
	Denier Change (%)	-3.8	-3.9	-4.1	-4.3
370-400°F	Weight Change (%)	-5.2	-4.1	-5.3	-10.7
	Length Change (%)	0	0	0	-1.1
	Denier Change (%)	-5.2	-4.1	-5.3	-9.8
570-600°F	Weight Change (%)	-5.6	-4.2	-5.1	-8.5
	Length Change (%)	0	0	0	-1.7
	Denier Change (%)	-5.6	-4.2	-5.1	-7.1
750°F	Weight Change (%)	-6.3	-5.6	-6.0	-8.5
	Length Change (%)	0	-2.2	-1.1	-20.0
	Denier Change (%)	-6.3	-3.4	-3.9	+14.2
800°F	Weight Change (%)	-6.3	-5.9	-6.4	-7.4
	Length Change (%)	-1.1	-2.2	-2.2	-26.7
	Denier Change (%)	-4.8	-4.4	-4.1	+26.3

5. Low Strain Rate (0.167%/sec) Tensile Test Results

Tensile data obtained at a strain rate of 0.167%/sec (10%/min), Instron testing machine) is presented in several ways, the most basic format being a series of stress-strain curves shown in Figures 5 through 8. Individual test results are tabulated in the Appendix, Table 22, and a summary of low strain rate properties is given in Table 3. Figures 9 through 12 contain plots of individual tensile properties versus test temperature. Included in both the summary table and property versus temperature curves are nylon and Nomex data obtained by FRL under previously referenced Air Force contracts*. Subambient and high-temperature data for these two materials were taken at different times using yarns that differed slightly in room temperature properties. Therefore, in order to permit meaningful comparisons throughout the temperature range, the subambient tenacity and elongation data shown for nylon and Nomex were adjusted slightly, based upon the ratios of the ambient data for the two sets of yarn.

*AFML Reports TR-68-279; TR-70-267, Part II.

TABLE 3

SUMMARY OF TENSILE PROPERTIES AT LOW STRAIN RATE (0.167%/sec)

Material	Temp (°F)	Actual Denier	Rupture Tenacity (gpd)	Rupture Tenacity (10^3 psi)	Rupture Elong (%)	Initial Modulus (gpd)	Initial Modulus (10^6 psi)	Energy to Rupture (gpd)	Energy to Rupture (10^3 psi)
Kevlar 29	- 65	1530	22.9	425	3.5	615	11.4	0.40	7.4
	70	1530	20.8	386	3.6	507	9.4	0.35	6.5
	200	1480	18.9	351	3.4	447	8.3	0.29	5.4
	400	1450	13.7	254	2.9	372	6.9	0.19	3.5
	600	1440	8.0	148	2.0	360	6.7	0.08	1.5
	800	1460	2.3	43	0.7	372	6.9	0.01	0.2
Kevlar 49	- 65	410	18.6	350	2.0	945	17.5	0.19	3.5
	70	410	18.5	340	2.2	841	15.6	0.20	3.7
	200	395	15.9	290	1.9	855	15.9	0.15	2.8
	400	395	10.3	190	1.5	764	14.2	0.08	1.5
	600	390	6.0	110	1.0	653	12.1	0.03	0.6
	800	390	4.3	80	0.8	509	9.4	0.02	0.4
PRD-49 IV	- 65	410	21.5	400	2.6	869	16.1	0.28	5.2
	70	410	18.7	350	2.6	746	13.8	0.24	4.5
	200	395	15.8	290	2.4	698	13.0	0.19	3.5
	400	395	10.5	190	2.0	591	11.0	0.11	2.0
	600	390	7.0	130	1.2	630	11.7	0.04	0.7
	800	390	5.0	92	0.8	563	10.4	0.02	0.4
PBI	- 65	210	6.3	111	9.8	145	2.5	0.44	8.2
	70	210	5.8	99	15.9	126	2.1	0.61	11.3
	200	195	7.1	125	16.2	120	2.0	0.71	13.2
	400	190	6.0	104	15.6	96	1.6	0.53	9.9
	600	190	4.1	70	15.0	79	1.3	0.36	6.7
	800	240	0.8	14	3.9	31	0.5	0.02	0.4
Nylon*	-109	1040	9.8	138	8.3	108	1.5	----	----
	70	1030	6.7	94	13.0	44	0.6	0.45	8.4
	200	1040	5.7	80	18.9	21	0.3	0.54	10.0
	400	1100	3.2	45	44.0	8	0.1	0.84	15.6
Nomex*	-109	1280	7.1	127	18.4	131	2.3	----	----
	70	1290	5.1	91	27.6	113	2.0	1.10	20.5
	200	1210	4.8	86	23.3	108	1.9	0.86	16.0
	400	1220	3.5	63	26.4	90	1.6	0.73	13.6
	600	1250	1.6	29	20.4	22	0.4	0.22	4.1

All data is based upon denier and gauge length values determined at each test temperature.
*1.67%/sec strain rate.

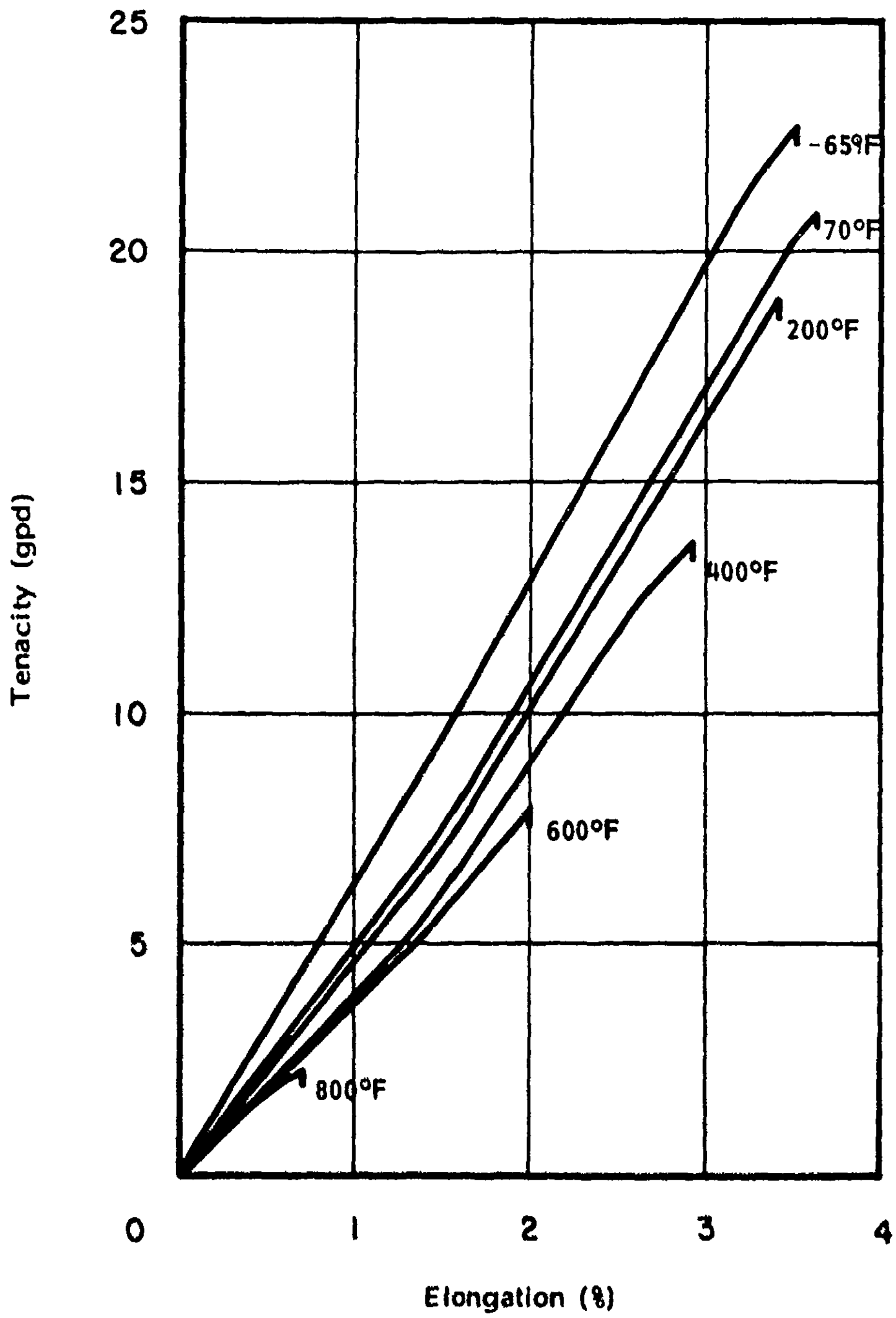

Figure 5. Stress-Strain Diagrams for Kevlar 29 Yarn Tested at a Strain Rate of 0.167%/sec (10%/min) at Various Temperatures (based upon at-temperature yarn dimensions)

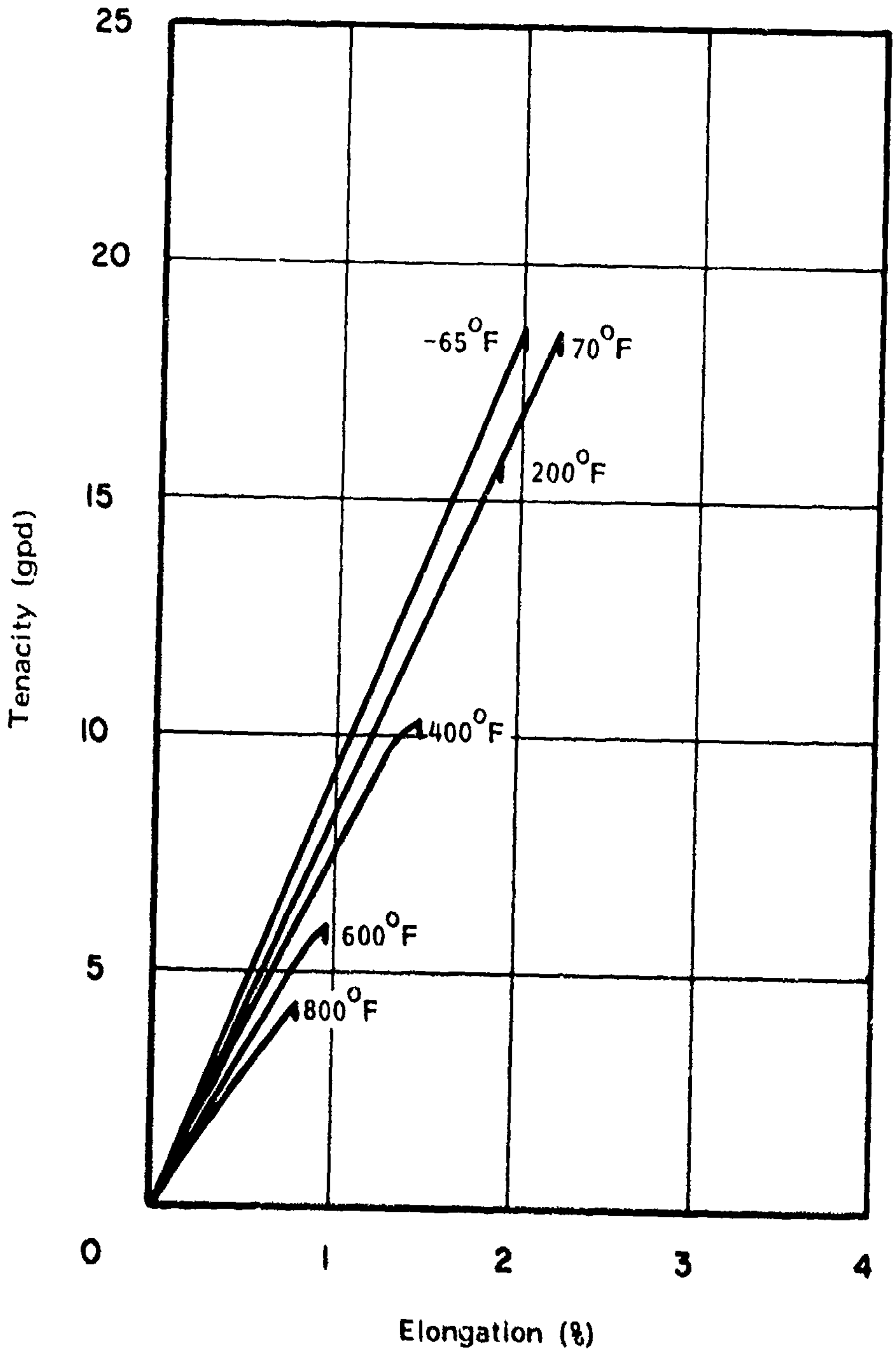

Figure 6. Stress-Strain Diagrams for Kevlar 49 Yarn Tensile Tested at a Strain Rate of 0.167%/sec (10%/min) at Various Temperatures (based upon at-temperature yarn dimensions)

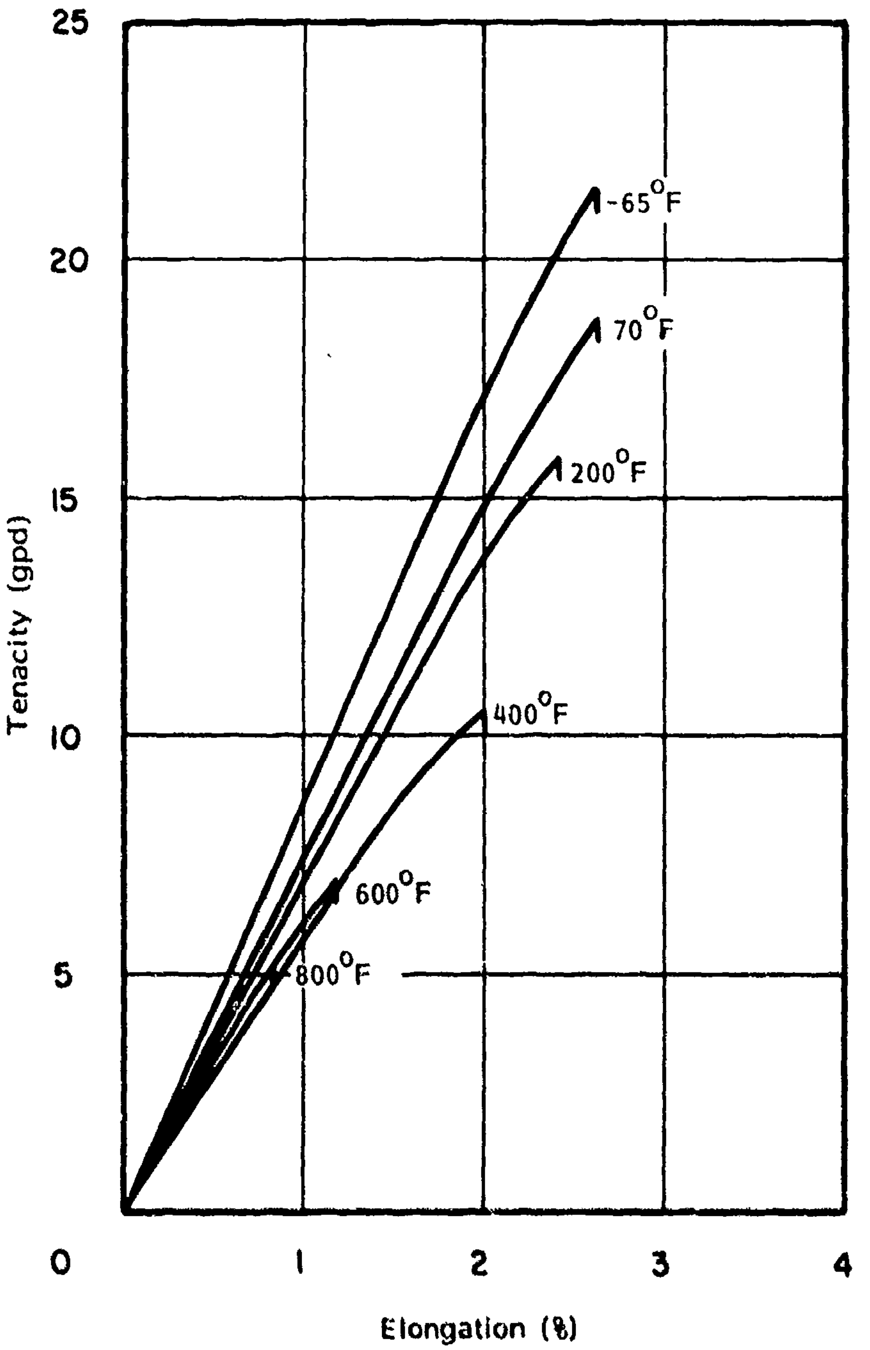

Figure 7. Stress-Strain Diagrams for PRD-49 IV Yarn Tensile Tested at a Strain Rate of 0.167%/sec (10%/min) at Various Temperatures (based upon at-temperature yarn dimensions)

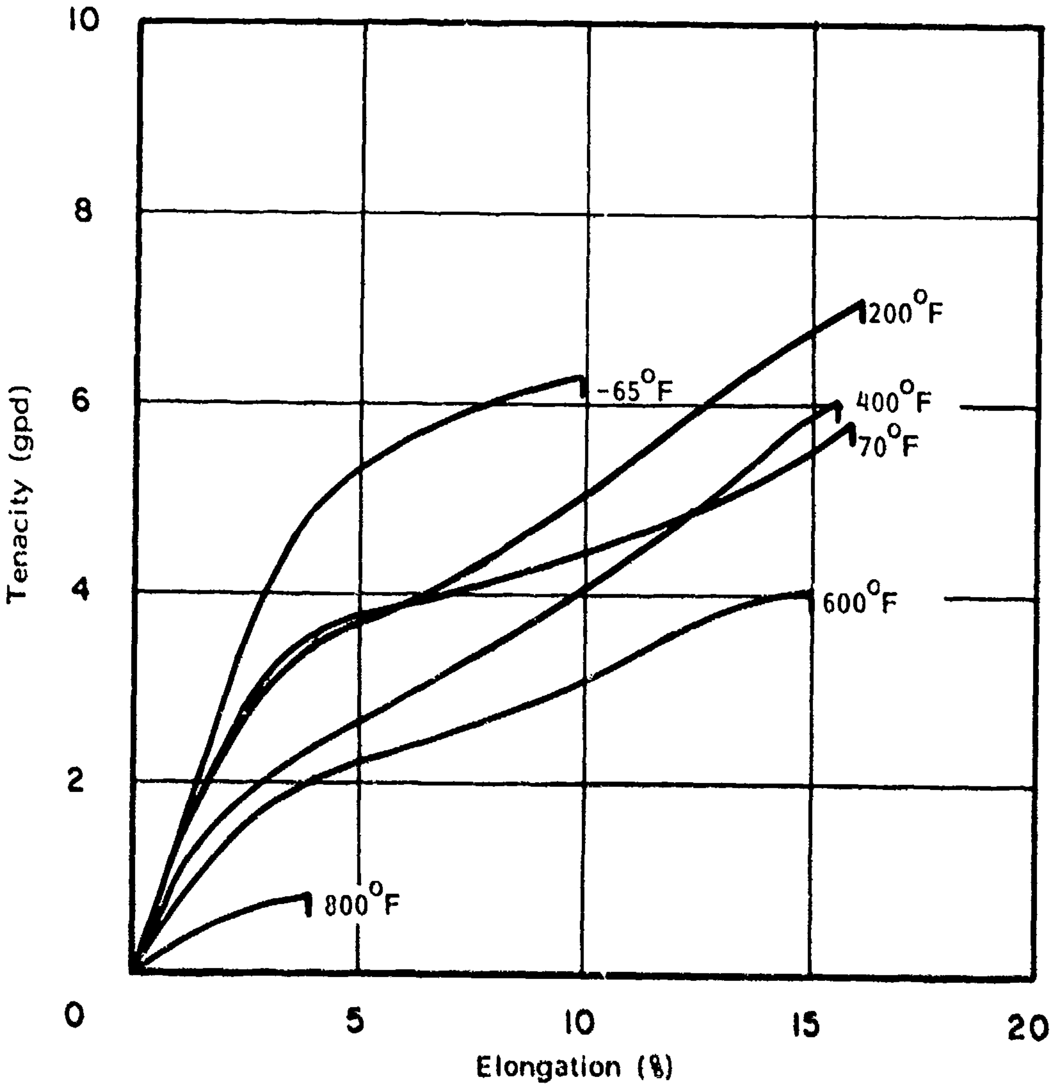

Figure 8. Stress-Strain Diagrams for PBI Yarn Tensile Tested at a Strain Rate of 0.167%/sec (10%/min) at Various Temperatures (based upon at-temperature yarn dimensions)

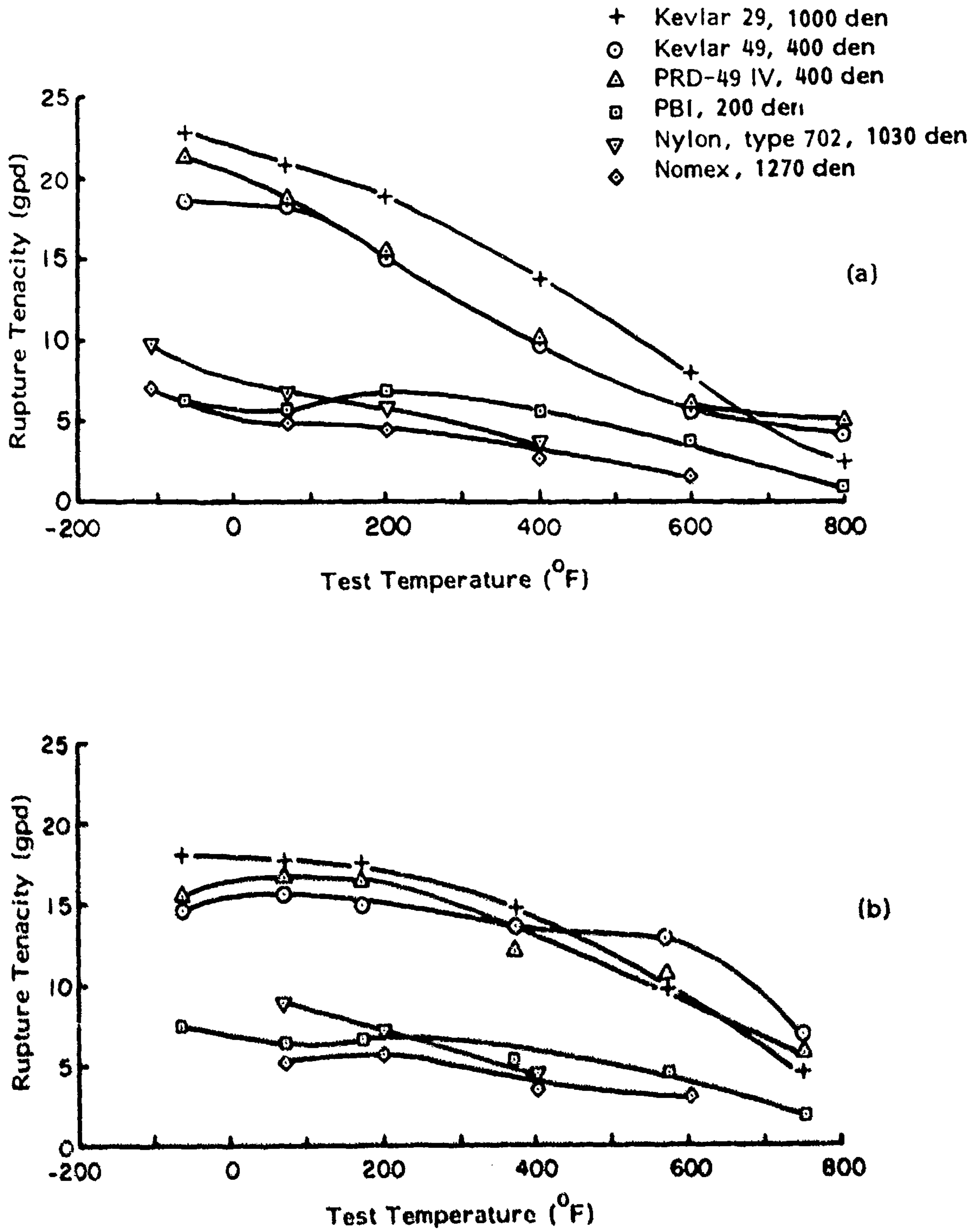

Figure 9. Rupture Tenacity as a Function of Tensile Test Temperature at (a) Low Strain Rate and (b) High Strain Rate (stress values based upon denier measured at 70°F)

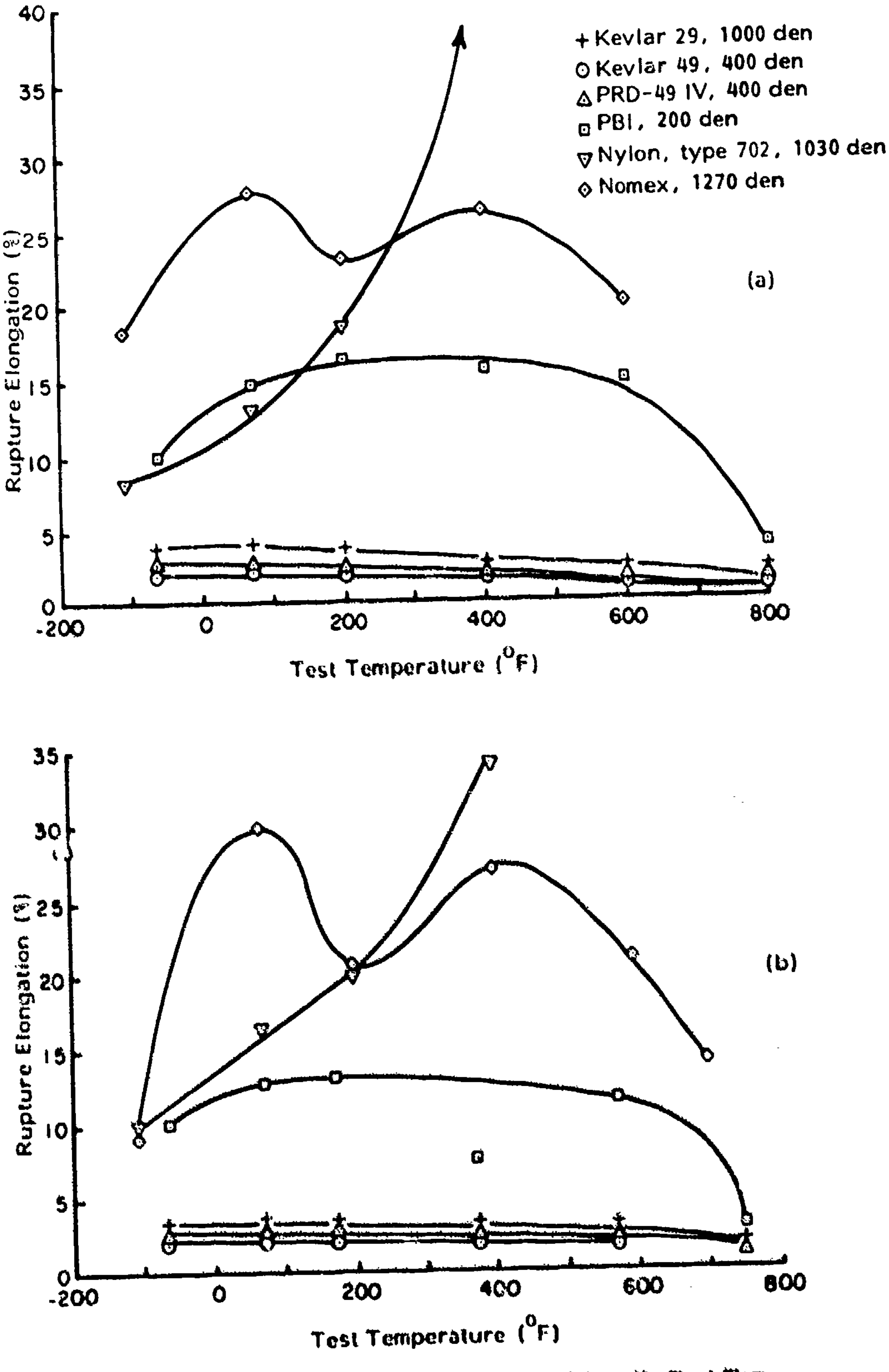

Figure 10. Rupture Elongation as a Function of Tensile Test Temperature at (a) Low Strain Rate and (b) High Strain Rate (based upon at-temperature yarn dimensions)

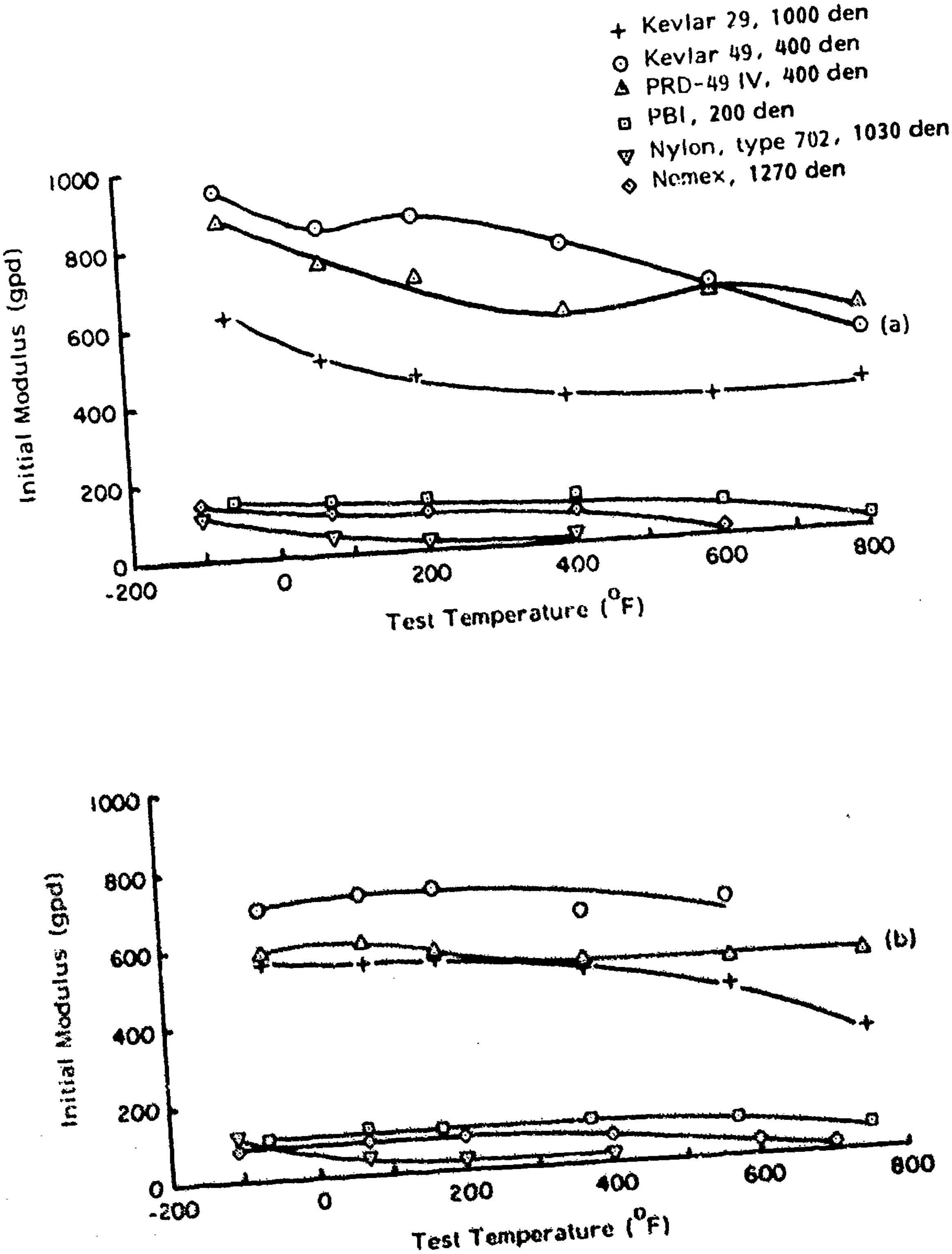

Figure 11. **Initial Modulus of Yarns as a Function of Tensile Test Temperature at (a) Low Strain Rate and (b) High Strain Rate (based upon at-temperature yarn dimensions)**

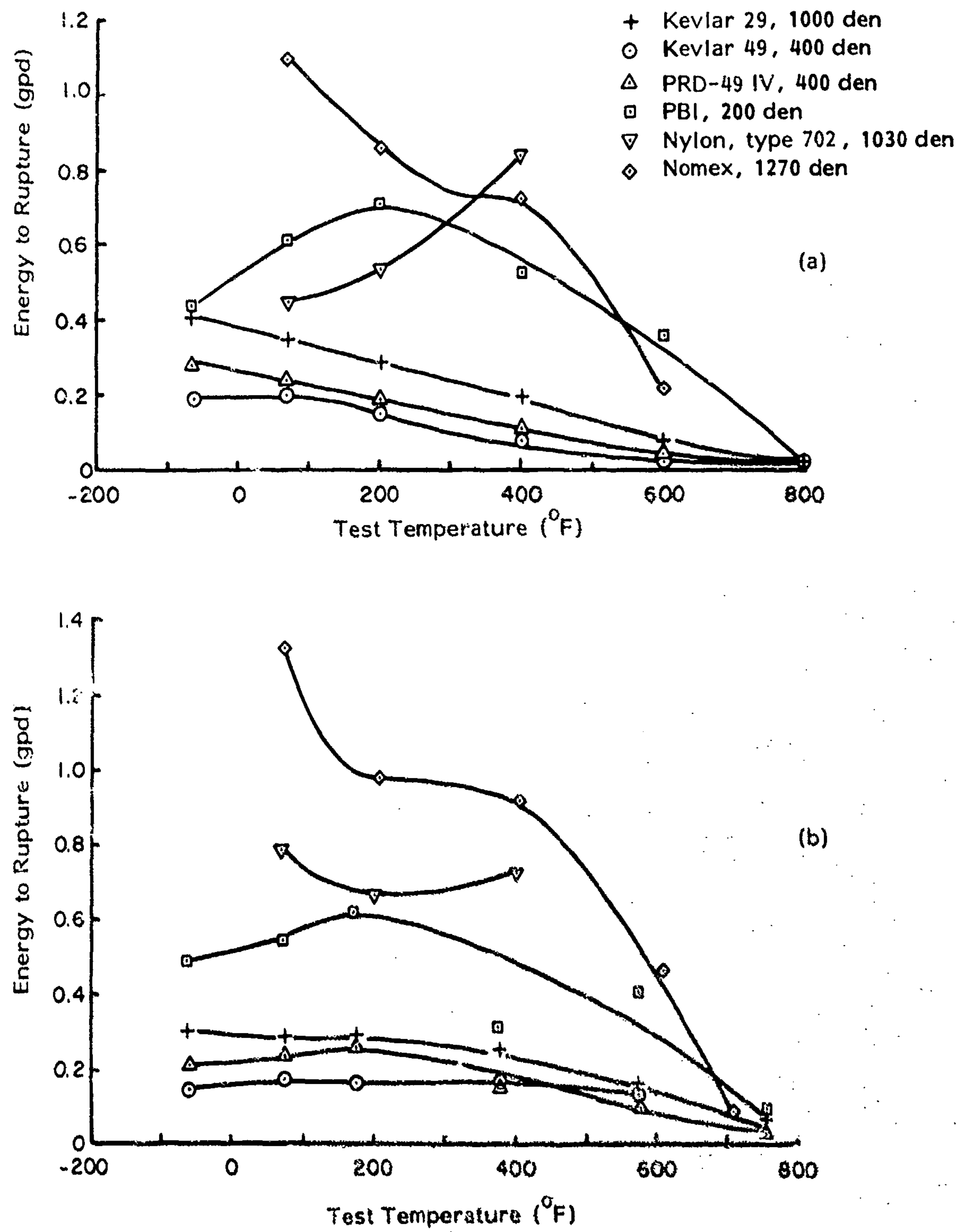

Figure 12. Energy to Rupture of Yarns as a Function of Tensile Test Temperature at (a) Low Strain Rate and (b) High Strain Rate (based upon at-temperature yarn dimensions)

The most prominent feature seen in the stress-strain plots (Figures 5 through 8) is the unique appearance of the Kevlar (Kevlar 29, Kevlar 49, and PRD-49 IV) curves. Notice, for example, that at 70°F all are nearly linear, and that all three rupture tenacities are greater than 18 gpd. Rupture elongation values are generally low, ranging from 2.2% for Kevlar 49 to 3.6% for Kevlar 29. These high tenacities and low elongation properties yield initial modulus values that are extraordinarily high, ranging from 507 gpd for Kevlar 29 to 841 gpd for Kevlar 49. For the sake of comparison, it is interesting to note initial modulus values for several other yarns: 44 gpd for Type 702 nylon, 300 gpd for stainless steel and 380 gpd for "S" glass. Also apparent from the stress-strain curves is the great strength retention of all four yarn types, including PBI, at elevated test temperatures up to 600°F. In contrast, nylon has melted at 489°F. Figures 9 through 12 show more directly the effect of temperature upon yarn properties. Additionally, these curves yield convenient comparisons of relative property values, including those for nylon and Nomex. It can be seen that, in the most general terms, the tensile properties of PBI, nylon, and Nomex form one group of curves and those for the three Kevlars form another. Numerous specific observations and comparisons may be made using these curves, but they are best left for the reader.

6. High Strain Rate (8000%/sec) Tensile Test Results

High strain rate (8000%/sec) tensile testing was done on FRL's pneumatically driven test machine using the same jaw system and gauge lengths employed for the low strain rate work. The same nominal test temperatures were used, but during the course of the testing, a temperature gradation was discovered in the oven being used. This oven, referred to previously, has interior dimensions of 3 inches by 3 inches by 25 inches high. Since the cross-sectional area is so small, the temperature-monitoring thermocouple was mounted approximately one-half inch from the oven wall, to avoid contact with the specimen during slack take-up. At 800°F, the upper temperature limit used for the work in the Instron testing machine, testing at high strain rate became an impossible task, as the integrity of all four materials was marginal. Rupture elongation values measured for the Kevlar yarns were less than 1%, and too small for measurement with currently available equipment (test duration at this testing speed was only 100-200 microseconds). Therefore, 750°F was adopted as the upper test temperature. Even at this level, the elongation measurements in one case, that of Kevlar 49, were not considered reliable enough to report. It is safe to say, however, that the true rupture elongation value for Kevlar 49 at 750°F lies within the range of 0.7 to 1.2%.

High strain rate tensile data is presented in tabular and graphical form similar to that for the corresponding low strain rate testing. Stress-strain curves appear as Figures 13 through 16. These plots also contain, for comparison, a stress-strain curve for the same yarn tested at 0.167%/sec at 70°F. Again, individual test results are tabulated in Appendix Table 23 and a summary of high strain rate properties is given in Table 4. Figures 9 through 12 show the effect of temperature upon each of four basic tensile properties for a total of six yarn materials at both high and low strain rates.

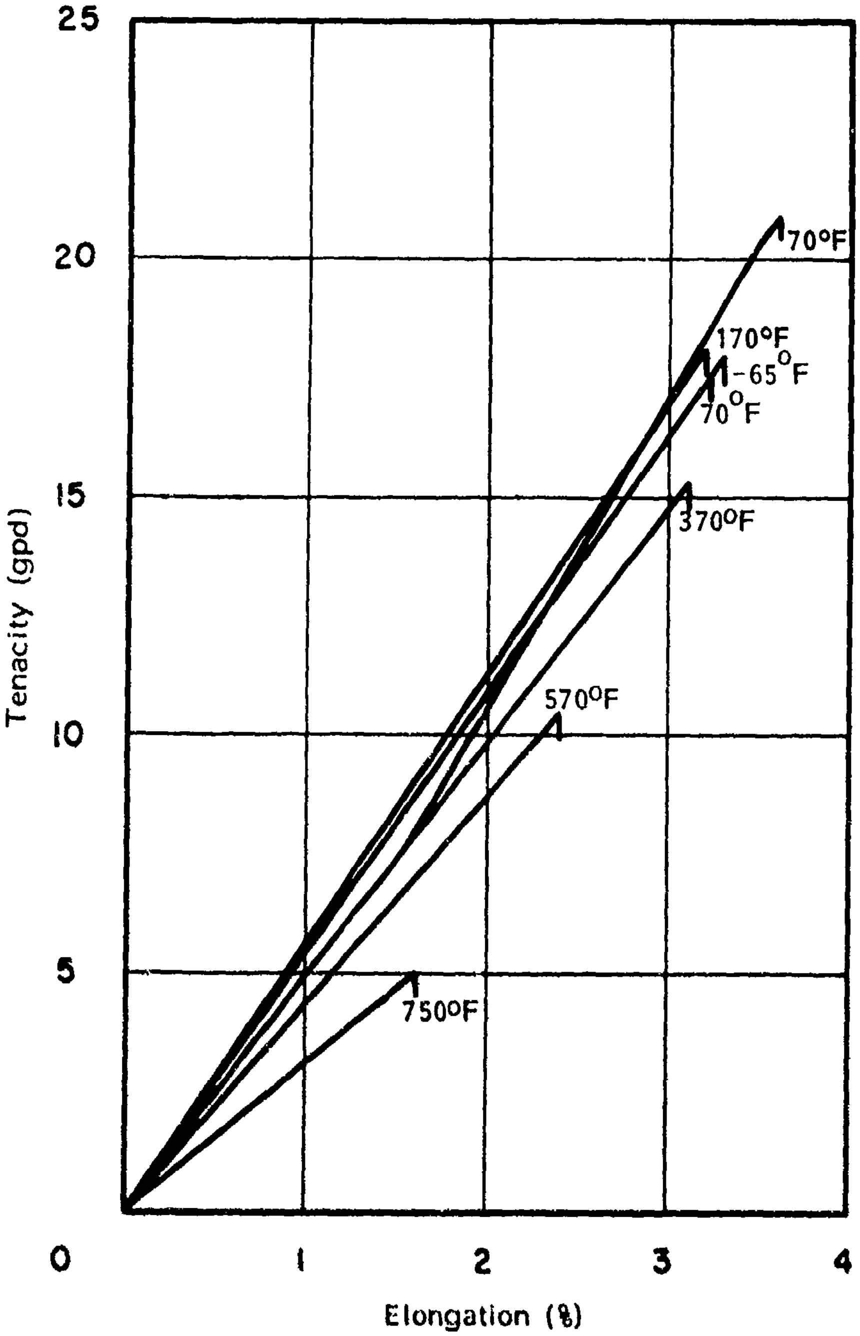

Figure 13. Stress-Strain Diagrams for Kevlar 29 Yarn Tensile Tested at a Strain Rate of 8000%/sec at Various Temperatures (based upon at-temperature yarn dimensions)

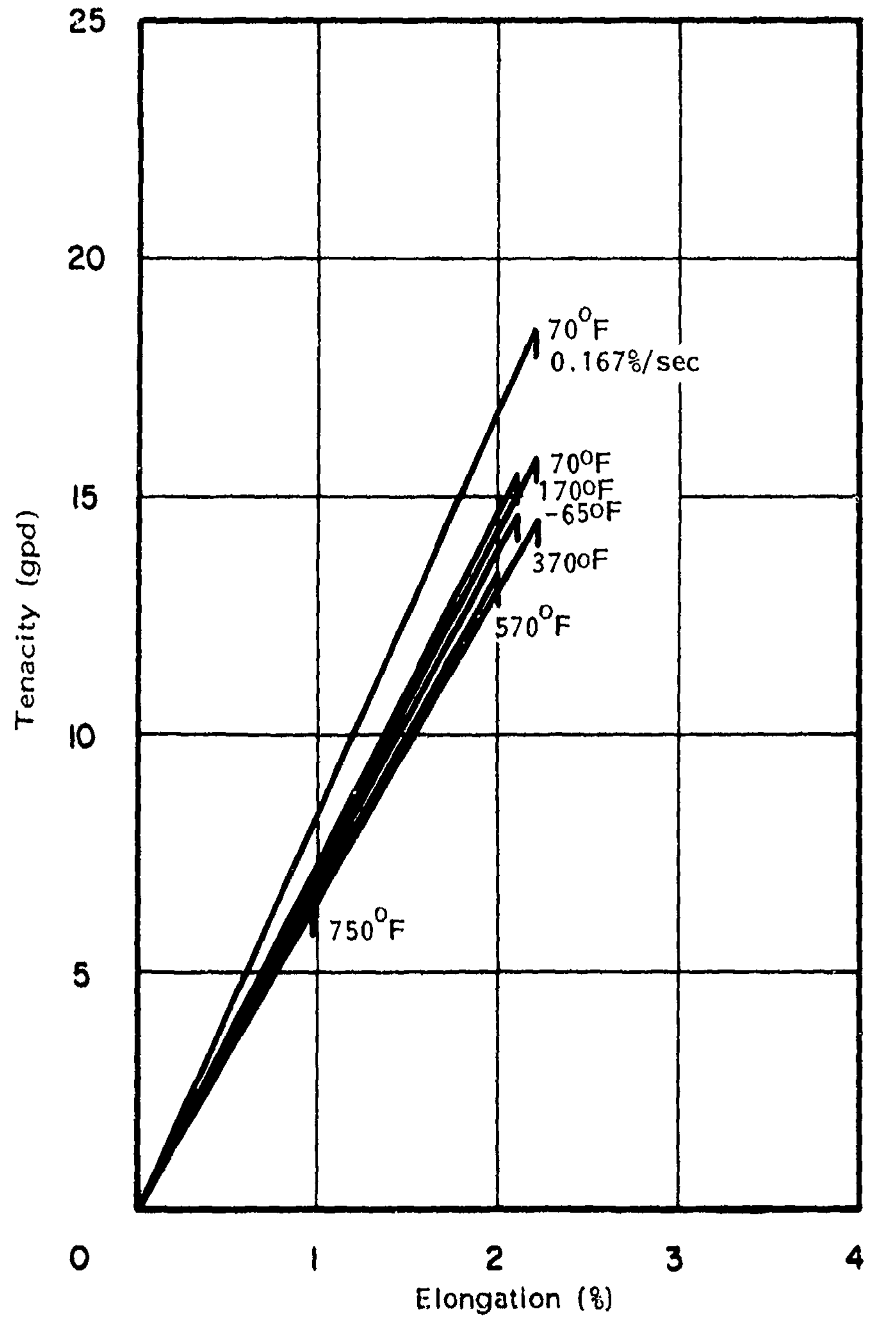

Figure 14. Stress-Strain Diagrams for Kevlar 49 Yarn Tensile Tested at a Strain Rate of 8000%/sec at Various Temperatures (based upon at-temperature yarn dimensions)

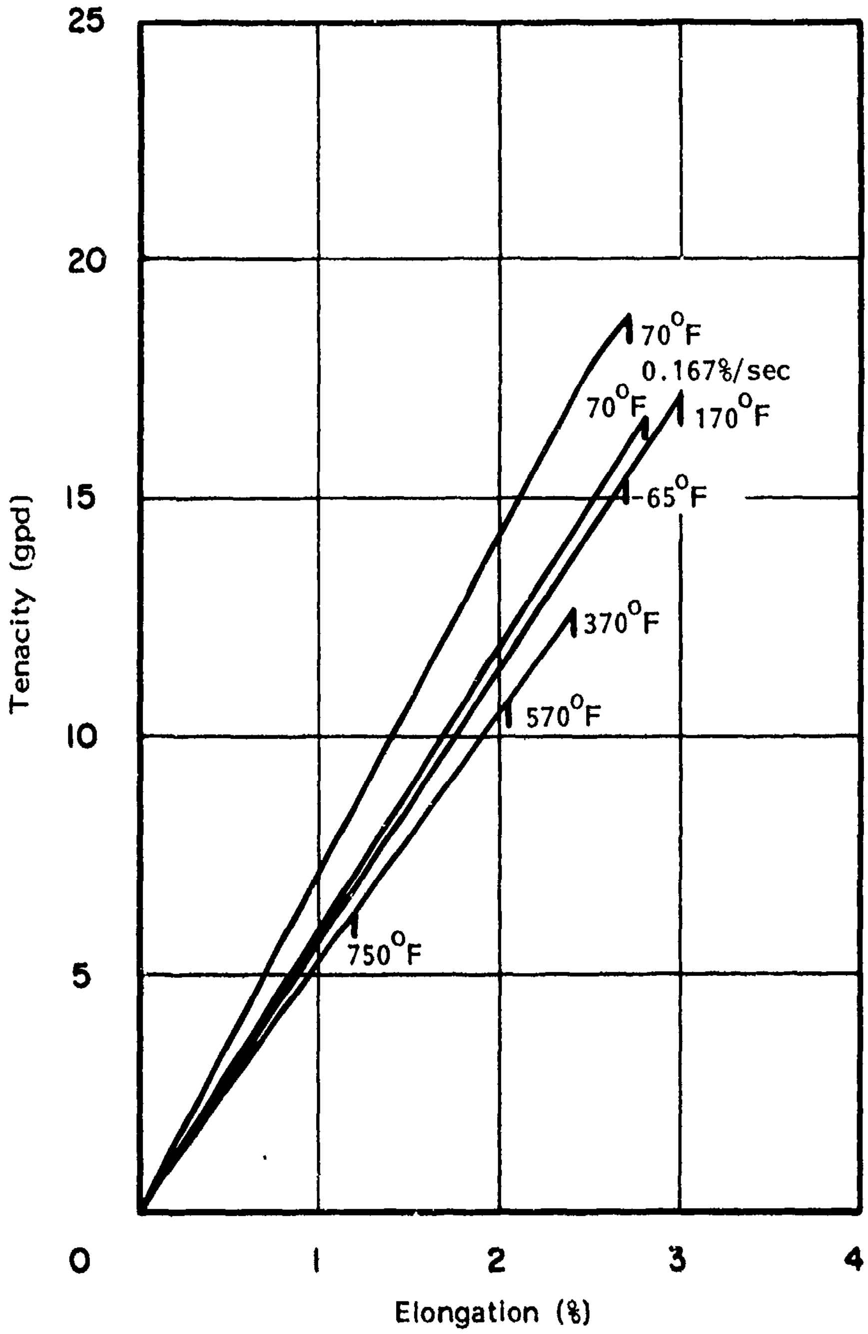

Figure 15. Stress-Strain Diagrams for PRD-49 IV Yarn Tensile Tested at a Strain Rate of 8000%/sec at Various Temperatures (based upon at-temperature yarn dimensions)

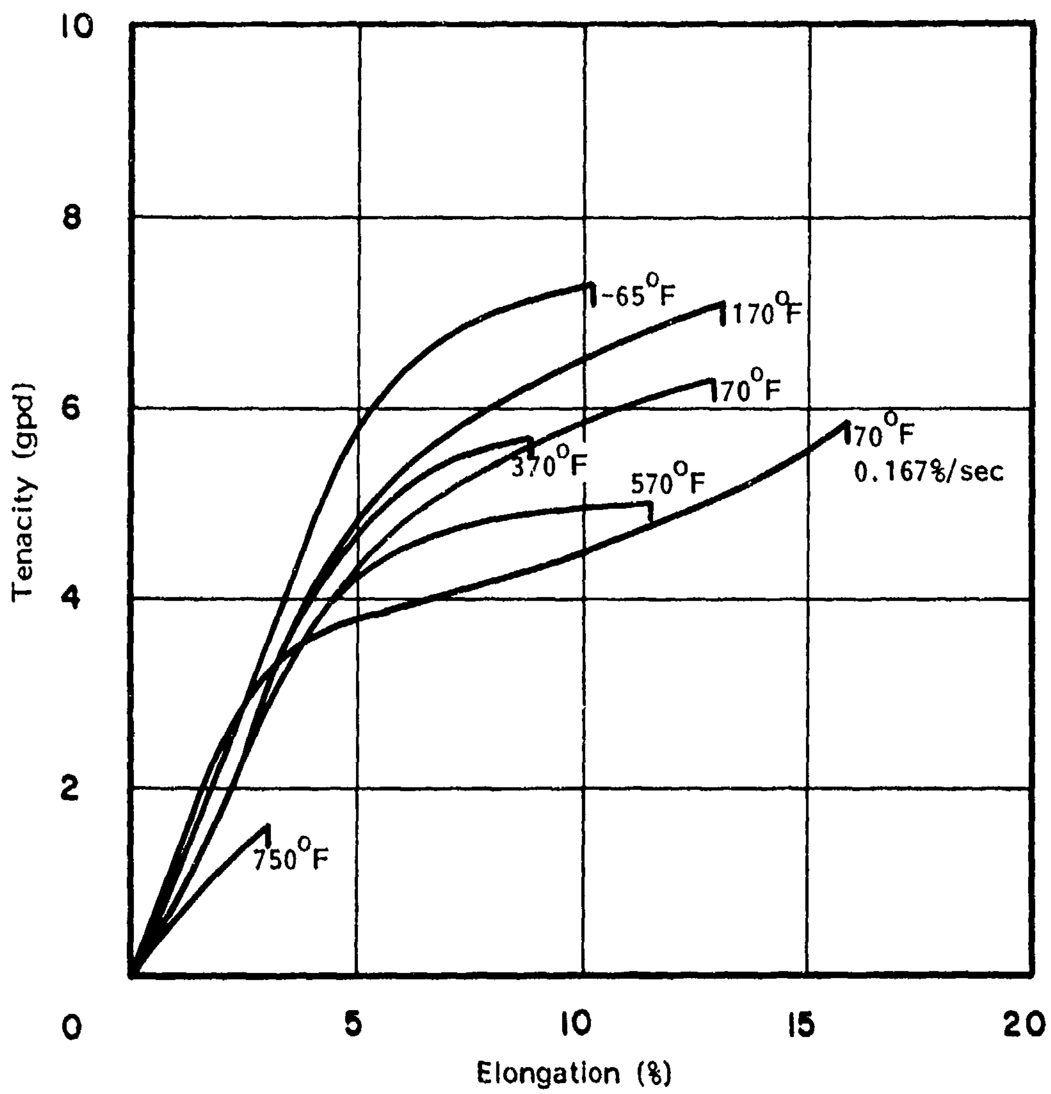

Figure 16. Stress-Strain Diagrams for PBI Yarn Tensile Tested at a Strain Rate of 8000%/sec at Various Temperatures (based upon at-temperature yarn dimensions)

Examining the stress-strain curves, Figures 13 through 16, it is worthwhile to note first the effect of strain rate alone on the yarns tested (disregarding temperature effects for the moment). At the higher strain rate, the three Kevlar yarns retain a generally linear appearance, rupture elongation values are essentially unchanged, and rupture tenacities are clearly lower. With straight line plots such as these, the net result of a lower tenacity and a minimal change in rupture elongation is, naturally, a reduction in the value of the initial modulus. The Kevlars appear to be unique in their response to high strain rate loading. The majority of commonly used textile materials react in a manner more similar to that seen in Figure 13 for PBI. With the change in strain rate from 0.167%/sec to 8000%/sec, the rupture tenacity of PBI increased approximately 8% and the rupture elongation decreased 19%.

Another pertinent observation regarding the effect of strain rate can be made from the plots of tensile properties versus test temperature (Figures 9-12). Notice that the effect of increasing temperature on the tensile properties of the Kevlars is distinctly less severe at the high rate of strain. In fact, these materials generally exhibit a remarkable degree of tensile integrity at high temperatures (600°F) and high strain rates (8000%/sec).

As suggested previously, the plots of individual tensile properties versus temperature emphasize the unusual character of the Kevlar series. Comparisons with the properties of PBI, nylon, or Nomex at either strain rate or at any temperature up to 600°F yield distinct differences in absolute values. The nature of these differences leads to the general characterization of the Kevlars as extremely high tenacity, low elongation, high modulus materials. A fourth relevant property, energy absorption, should also be examined. From Figure 12 it is apparent that nylon, Nomex, and PBI all absorb more energy to rupture than any of the Kevlar series. The differences are, in general, quite large and are greater at the high strain rate. It should be noted that the energy absorption values shown for Type 702 nylon are unusually low in comparison with other published data for nylon and thus do not yield a truly representative comparison in this case. And, since the unusually high tenacity of the Kevlars may render them potential replacements for nylon in many high impact applications, energy absorption is a vital consideration. However, FRL recently conducted an extensive series of tensile tests on various types of nylon yarn and the information obtained can be used to provide a comprehensive comparison of Kevlar properties with those of many types of nylon. This project was performed under contract to U. S. Army Natick Labs and the majority of the data shown in Tables 5 and 6 is copied, with their permission, from QM Technical Report No. 73-60-CE. Comparing energy to rupture values contained in these tables, it can be seen that at both high and low strain rates, high tenacity nylon yarn generally absorbs two to three times the energy of the Kevlars during a test to failure.

TABLE 4

SUMMARY OF TENSILE PROPERTIES AT HIGH STRAIN RATE (8000%/sec)

Material	Temp (°F)	Actual Denier	Rupture Stress (gpd)	Rupture Stress (10^3 psi)	Rupture Elong (%)	Initial Modulus (gpd)	Initial Modulus (10^6 psi)	Energy to Rupture (gpd)	Energy to Rupture (10^3 psi)
Kevlar 29	- 65	1530	18.0	330	3.3	550	10.2	0.30	5.5
	70	1530	17.5	320	3.2	550	10.1	0.28	5.2
	170	1480	18.1	330	3.2	560	10.3	0.29	5.4
	370	1450	15.3	280	3.1	550	9.2	0.24	4.4
	570	1440	10.5	190	2.4	440	8.1	0.13	2.4
	750	1430	5.0	93	1.6	310	5.8	0.04	0.7
Kevlar 49	- 65	410	14.6	270	2.1	700	13.0	0.15	2.8
	70	410	15.8	290	2.2	720	13.4	0.17	3.1
	170	395	15.5	290	2.1	730	13.4	0.16	3.0
	370	395	14.5	270	2.2	650	12.0	0.16	3.0
	570	390	13.4	250	2.0	670	12.3	0.13	2.4
	750	390	6.5	120	---	---	----	----	---
PRD-49 IV	- 65	410	15.4	290	2.7	580	10.8	0.21	3.9
	70	410	16.7	310	2.8	600	11.0	0.23	4.3
	170	395	17.2	320	3.0	570	10.5	0.26	4.8
	370	395	12.7	230	2.4	520	9.6	0.15	2.8
	570	390	10.7	200	2.1	510	9.4	0.11	2.0
	750	390	6.2	115	1.2	510	9.4	0.04	0.7
PBI	- 65	210	7.3	124	10.1	110	1.9	0.49	8.3
	70	210	6.3	107	12.9	110	1.9	0.55	9.4
	170	195	7.1	121	13.1	110	1.9	0.62	10.5
	370	190	5.7	97	7.3	110	1.9	0.31	5.2
	570	190	5.0	85	11.5	100	1.7	0.41	7.0
	750	240	1.6	27	3.0	64	1.1	0.03	0.5
Nylon**	-109	1040	8.8	128	10.0	100	1.5	----	----
	70	1030	8.9	130	16.6	56	0.8	0.79	11.5
	200	1040	7.0	102	20.2	26	0.4	0.67	9.8
	400	1100	3.9	57	34.3	15	0.2	0.73	10.7
Nomex**	-109*	1280	5.8	104	8.8	87	1.6	----	----
	70	1270	5.2	93	30.2	92	1.6	1.33	5.9
	200	1210	5.7	102	21.9	94	1.7	0.98	17.5
	400	1220	4.4	79	27.2	71	1.3	0.92	16.5
	600	1250	3.1	55	21.4	45	0.8	0.46	8.2
	700	1270	1.5	27	14.4	11	0.2	0.09	0.3

All data is based upon denier and gauge length values determined at each test temperature.

*3000%/sec strain rate at -109°F.

**The nylon and Nomex curves passed through a stress maximum prior to rupture. The rupture tenacities given correspond to the point of maximum stress, while the rupture elongations and energies to rupture correspond to the points of rupture.

TABLE 5

COMPARISON OF LOW STRAIN RATE* TENSILE PROPERTIES (at 70°F)
OF VARIOUS TYPES OF NYLON YARN WITH
THOSE OF KEVLAR 29 AND KEVLAR 49 YARN

Yarn	Tenacity (gpd)	Rupture Elongation (%)	Initial Modulus (gpd)	Energy to Rupture (gpd)
Nylon, du Pont				
330 High Tenacity				
420-68-1Z	7.76	16.8	37.3	0.74
70-34-1/2Z	6.94	18.8	47.2	0.84
728 High Strength				
840-140-R20	9.25	19.4	32.8	0.83
702 Bright Ind				
840-140-1/2Z	8.44	19.2	40.4	0.90
714 Bright Ind				
840-140-R20	8.82	19.2	38.3	0.88
Nylon, Allied				
1Q70 High Tenacity				
840-136-1/2Z	8.87	20.2	35.4	0.92
Nylon, Monsanto				
A07 High Tenacity				
840-140-1/3Z	10.0	16.2	50.0	0.72
A05 High Tenacity Fatigue Resistant				
840-140Z	8.74	18.5	44.2	0.77
A06 High Strength Improved Durability				
840-140-Z	8.57	19.5	43.1	0.82
E02 High Tenacity				
840-68-1/2Z	8.17	17.0	45.7	0.71
Nomex, du Pont				
430 Regular				
200-100-0	5.27	22.0	121.0	0.89
Kevlar 29				
1500-1000-0	20.8	3.6	507	0.35
Kevlar 49				
400-267-0	18.5	2.2	841	0.20

*Nylon strain rate: 1.67%/sec; Kevlar strain rate: 0.167%/sec.

TABLE 6

COMPARISON OF HIGH STRAIN RATE (7000%-8000%/sec)
TENSILE PROPERTIES (at 70°F) OF VARIOUS TYPES OF NYLON YARN
WITH THOSE OF KEVLAR 29 AND KEVLAR 49 YARN

Yarn	Rupture Tenacity (gpd)	Rupture Elongation (%)	Initial Modulus (gpd)	Energy to Rupture (gpd)
Nylon, du Pont 330				
420-68-1Z	9.2	13.2	109	0.65
70-34-Z	7.9	14.7	94	0.71
Nylon, du Pont 702				
840-140-1/2Z	9.6	16.4	117	0.77
Nylon, du Pont 728				
840-140-R20	10.2	16.3	108	0.73
Nylon, Monsanto A07				
840-140-1/3Z	10.9	14.6	135	0.61
Kevlar 29				
1500-1000-0	17.5	3.2	550	0.28
Kevlar 49				
400-267-0	15.8	2.2	720	0.17

7. Variability of Kevlar 29 Yarn

All of the results reported herein were obtained from yarn from one package, so that one might expect comparisons showing the effect of strain rate or of temperature to be unaffected by variability. Some indication of the effect of yarn denier, between package variability, or merge on the comparisons obtained was examined in the case of Kevlar 29.

A similar set of tests at low strain rates and all temperatures were carried out on 1000 instead of 1500 denier yarn. Instron (low strain rate) tests at 70°F were also carried out on 2 packages each of 1000 and 1500 denier yarn from another merge. The results are given in Tables 7 and 8.

The results in Table 7 show that, in general, 1000 denier yarn has a higher tenacity and, perhaps, somewhat higher modulus than 1500 denier yarn. Differences between yarn of the same denier are primarily in the value of the initial modulus, which seems to vary as much as 20%. The between package variability within a merge is very low.

TABLE 7

VARIABILITY OF KEVLAR 29 YARN AT 70°F, 0.167%/SEC STRAIN RATE

Yarn Identification	Merge No.	Package No.	Actual Denier	Rupture Tenacity (gpd)	Rupture Elong (%)	Initial Modulus (gpd)
unidentified 1500 denier used in all previous tensile tests	--	-	1530	20.8	3.6	507
1500-1000-R80-964	6F016	1	1560	19.6	3.5	461
		2	1560	19.6	3.4	467
unidentified 1000 denier	--	--	1030	22.2	3.4	585
1000-666-R80-964	6F028	1	1020	22.4	3.7	481
		2	1000	20.8	3.6	493

TABLE 8

TENSILE PROPERTIES OF 1000 AND 1500 DENIER KEVLAR 29 YARN, 0.167%/SEC STRAIN RATE

Yarn Denier	Temperature (°F)	Rupture Tenacity (gpd)	Rupture Elongation (%)	Initial Modulus (gpd)
1030	-65	23.2	3.6	627
1030	70	22.2	3.4	585
990	200	19.2	3.1	564
975	400	14.5	2.6	510
970	600	7.0	1.5	457
980	800	3.1	0.8	343
1530	-65	22.9	3.5	615
1530	70	20.8	3.6	507
1480	200	18.9	3.4	447
1450	400	13.7	2.8	372
1440	600	8.0	2.0	360
1460	800	2.3	0.7	372

Differences in tenacity between the deniers are shown in Table 8 to be larger at 70°F than at other temperatures. Again, the biggest difference between 1000 and 1500 denier yarn at all temperatures is in the value of the initial modulus.

The absolute values of the quantities studied in all of this work must be interpreted with this variability in mind. It is clear that the yarn tested was different, particularly in the value of its modulus, from more recent yarn represented by merge numbers 6F016 and 6F028. However the yarns from these two merges are very similar, in spite of their denier differences. It is safe to say that the general trends resulting from changes in temperature or strain rate are reliable, but the absolute value of the tensile parameters, or of changes therein, may depend upon the particular yarn package being tested.

8. Summary of Tensile Characteristics of Kevlar and PBI Yarns

Yarns of Kevlar 29, Kevlar 49, PRD-49 IV, and PBI were tensile tested under a total of twelve conditions each. Operating at strain rates of 0.167%/sec (10%/min) and 8000%/sec, six temperature levels were employed, ranging from -65 to 800°F. A large collection of data was thus obtained. To facilitate worthwhile examination of this information, it has been presented in several graphic and tabular forms, together with comparable data for nylon and Nomex yarn, obtained in the course of earlier Air Force programs. A thorough study of these test results will undoubtedly reveal a number of specific observations and comparisons of value. Consideration of the most relevant facts to be observed in the entire data compilation leads to the following observations:

1. Under the most basic test conditions (a strain rate of 0.167%/sec and at 70°F), the tensile properties of the Kevlar yarns differ greatly from those of PBI, nylon, and Nomex. In comparison with this latter group of yarn materials, the Kevlars exhibit very high tenacity, low elongation, high initial modulus, and low energy absorption.

2. When the rate of strain is increased to 8000%/sec at 70°F, the tensile behavior of the Kevlars remains somewhat unique. Tenacity drops an average of 14% and rupture elongation is virtually unchanged. The high strain rate behavior of PBI is more typical of that associated with previously known textile materials. At 8000%/sec, the tenacity of PBI increased 8% and the rupture elongation decreased 21%.

3. All four yarn types retained useful tensile properties up to approximately 600°F. Above this temperature rupture elongation and, therefore, rupture energy, fall off drastically, though significant strength was retained even at 800°F.

4. At elevated temperatures, the high strain rate tensile performance of the Kevlars is generally superior to that recorded at Instron testing speeds.

5. At a temperature of -65°F, both high and low strain rate testing of Kevlar yarn revealed only minor changes in tensile properties from those at 70°F. However, PBI, Nylon, and Nomex are affected by subambient temperatures when tested at 0.167%/sec, all three showing significant increases in tenacity and decreases in rupture elongation. At the higher strain rate, the effect of subambient temperatures on PBI, nylon, and Nomex becomes a much less important factor.

6. The great potential of Kevlar 29 as an improved replacement for nylon in many high impact, high temperature applications has been noted previously. However, the low level of energy absorption available with Kevlar 29 may limit this potential in certain cases. Due to vast differences in the tensile properties of Kevlar 29 and nylon, each design application would merit a thorough review before substitution with Kevlar 29 is made.

SECTION III

CRITICAL IMPACT VELOCITY

Critical velocity is defined as the lowest impact velocity at which the specimen, in this case a yarn, fails immediately at the point of impact. It is the lowest striking velocity at which there is no strain propagation away from the point of impact. The specimen, therefore, breaks without absorbing any of the kinetic energy of the impacting mass.

Critical velocity is determined using a .22 caliber, smooth-bore rifle and a notched bullet. Before striking the sample, the bullet breaks a tinfoil strip, electrically triggering an EG&G Multi-Microflash unit which emits fifteen separate, high-intensity light flashes, each with a duration of approximately one microsecond. The time interval between flashes, which is adjustable, is usually on the order of 20 to 30 microseconds. The position of both the bullet and the test specimen before, during, and after impact is recorded on a multiple exposure Polaroid print via open-shutter photography in a darkened room. After striking the specimen, the bullet passes through a timing trap and its velocity is recorded. For experimental purposes, critical velocity is taken to be that impact velocity at which rupture of the specimen occurs at the point of impact within 20 to 30 microseconds after impact. By making a number of tests over a range of impact velocities, it is possible to determine the velocity at which the test specimen ruptures before the second exposure after impact, i.e., within 20 to 30 microseconds after impact. This impact velocity is the critical velocity.

Both lateral impact ($\beta = 90°$) and 45° impact ($\beta = 45°$) critical velocities were determined for four yarn types: Kevlar 29, Kevlar 49, PRD-49 IV, and PBI. This data is reported in Table 9. Critical velocity level is generally regarded as an indicator of tensile impact performance. For example, du Pont Type 702 industrial nylon, frequently selected for use in situations where energy absorption at high strain rates is a vital requirement, has a relatively high lateral critical velocity of approximately 2000 fps. On the other hand, high modulus fibers such as glass, Thornel, Chromel R, and stainless steel all have relatively low lateral critical velocities, i.e., less than 1000 fps, and the energy absorbing capabilities of these fibers at high strain rates are also low. The lateral critical velocities reported in Table 9 for Kevlar 29, Kevlar 49, and PRD-49 IV (1875, 1625, and 1750 respectively) are high enough to suggest successful application of these materials in high strain rate situations. And it is particularly significant that these high modulus, low elongation fibers have critical velocity values much closer to that of nylon than to those of other available high modulus fibers. Although the relatively low energy absorption of the Kevlars (see Figure 12) may be a drawback in certain instances, the high tenacity, high modulus, and high critical velocity values measured indicate suitability in applications requiring improved impact performance.

TABLE 9

CRITICAL VELOCITY TEST DATA (fps)

	β = 90°		β = 45°	
Kevlar 29 1000 denier	1610	Well below critical	706	Well below critical
	1628	Below critical	741	Just below critical
	1785	Below critical	784	Critical
	1868	Near critical	823	Just above critical
	1873	Near critical	835	Above critical
	1922	Just above critical	904	Above critical
	1936	Above critical		
	Critical velocity: 1875 fps ± 50		Critical velocity: 775 fps ± 50	
Kevlar 49 400 denier	1178	Well below critical	598	Well below critical
	1518	Well below critical	673	Well below critical
	1535	Well below critical	714	Below critical
	1549	Well below critical	746	Critical
	1581	Near critical	788	Above critical
	1590	Near critical	794	Above critical
	1594	Near critical	915	Well above critical
	1685	Near critical		
	1697	Near critical		
	1712	Above critical		
	1722	Above critical		
	2500	Above critical		
	Critical velocity: 1625 fps ± 50		Critical velocity: 740 fps ± 50	
PRD-49 IV 400 denier	1502	Well below critical	652	Well below critical
	1688	Below critical	673	Well below critical
	1696	Near critical	698	Below critical
	1712	Near critical	726	Below critical
	1722	Near critical	754	Near critical
	1750	Critical	760	Near critical
	1804	Just above critical	796	Near critical
	1812	Above critical	844	Above critical
	1859	Above critical	849	Above critical
	1882	Above critical	864	Well above critical
	Critical velocity: 1750 fps ± 50		Critical velocity: 775 fps ± 50	
PBI 200 denier	1312	Well below critical	604	Well below critical
	1428	Just below critical	605	Well below critical
	1449	Critical	632	Below critical
	1496	Just above critical	719	Below critical
	1562	Above critical	723	Near critical
	1638	Above critical	734	Near critical
			738	Near critical
			805	Above critical
	Critical velocity: 1450 fps ± 50		Critical velocity: 725 fps ± 50	

SECTION IV

FIBER PROPERTIES

1. Specific Gravity of Kevlar and PBI Fibers

Measurements of the specific gravity of Kevlar 29, Kevlar 49, PRD-49 IV and PBI fibers were made in a density gradient column. The results are given in Table 10.

TABLE 10

SPECIFIC GRAVITY OF FOUR FIBERS

Material	Specific Gravity
Kevlar 29	1.45
Kevlar 49	1.45
PRD-49 IV	1.45
PBI	1.33

2. Diameter of Kevlar Fibers

The diameter of Kevlar 29 and Kevlar 49 fibers was measured using a projection microscope. Over 20 individual measurements on each material yielded the same result: 12µm or 0.00047 inch. The precision of this measurement is ±0.5µm or 0.00002 inch.

The fiber denier calculated from this value of diameter and the specific gravity is 1.5 for both Kevlar 29 and Kevlar 49.

3. Moisture Regain of Kevlar Fibers at 70°F, 65%RH

The moisture regain of Kevlar 29 and Kevlar 49 was determined according to ASTM Test Method D1909. The specimens were dried at 105°C for 2 hours, weighed, allowed to condition to a 70°F, 65%RH atmosphere for 48 hours, then weighed again. The values obtained are given in Table 11.

TABLE 11

MOISTURE REGAIN OF KEVLAR FIBERS AT 70°F, 65%RH

Material		Moisture Regain (%)
Kevlar 29		3.9
		3.9
		3.8
	Avg	3.9
Kevlar 49		4.6
		4.6
		4.5
	Avg	4.6

4. Tensile Properties of Kevlar Fibers

The tensile properties of Kevlar 29 and Kevlar 49 fibers were measured at 70°F and 0.167%/sec (10%/min) strain rate in order to determine the translational efficiency of fiber to yarn properties. The fibers tested were removed from those packages of untwisted yarn supplied for the investigation of twist on yarn properties; these were not the same packages of yarn used in the evaluation of yarn tensile properties at various temperatures and testing speeds.

The fibers were mounted on cardboard tabs with Epon 820 epoxy cement for testing.

A summary of the data obtained is given in Table 12; individual test data is contained in Table 24 of the Appendix.

TABLE 12

SUMMARY OF TENSILE PROPERTIES OF KEVLAR FIBERS
(70°F, 0.167%/sec)

Material	Gauge Length (inch)	No. of Tests		Initial Modulus (gpd)	Maximum Modulus (gpd)	Rupture Elong (%)	Rupture Tenacity (gpd)
Kevlar 29	1.0	13	Avg	---	---	4.4	26.9 (499)
			Range			4.0-4.9	24.0-29.0
			CV(%)			7.2	5.5
	3.0	29	Avg	564 (10.5)	703 (13.0)	4.1	26.7 (495)
			Range	463-656	643-768	3.5-4.6	23.6-29.1
			CV(%)	10.6	5.0	8.0	4.4
	5.0	30	Avg	546 (10.1)	755 (14.0)	3.9	25.6 (475)
			Range	420-651	657-812	3.6-4.4	21.9-28.6
			CV(%)	11.0	5.7	4.7	6.4
Kevlar 49	1.0	17	Avg	---	---	2.7	26.2 (486)
			Range			2.1-3.1	20.6-32.0
			CV(%)			11.4	12.9
	5.0	18	Avg	989 (18.4)	1088 (20.2)	2.3	23.8 (442)
			Range	910-1061	1039-1136	1.9-2.8	19.0-28.2
			CV(%)	4.0	2.5	10.9	11.3

The numbers in parentheses give the modulus in 10^6 psi units, or the rupture stress in 10^3 psi units.

2

Various lengths of fiber were tested to determine whether a machine compliance correction should be applied to the data; it was not necessary. However, a discrepancy in the initial modulus values of Kevlar 29 obtained at gauge lengths of 3.0 and 5.0 inches was apparent which led to further testing at these gauge lengths. (A modulus determination for a gauge length of 1.0 inch is not considered sufficiently precise to report.)

Reference to Table 24 in the Appendix shows the separate averages for two groups of tests on Kevlar 29 at both 3.0 and 5.0 inch gauge lengths; the average initial modulus of test group II at a 3.0 inch gauge length agrees with that of test group I at a 5.0 inch gauge length; similarly, the average initial modulus of test group I at a 3.0 inch gauge length is in close agreement with that of test group II at a 5.0 inch gauge length. The Student's-t test for the difference between two means indicates a significant difference at the 97.5% confidence level between the average initial modulus values of the two groups at the two gauge lengths. The mean rupture tenacities of the two groups are not significantly different at this confidence level at either gauge length; the average rupture elongations measured at 3.0 inches are significantly different while those measured at 5.0 inches are not. The property values listed in the summary table represents composite averages and CV's of the data from the separate test groups.

Thus, the initial modulus of Kevlar 29 fibers varies widely both between test groups as indicated by significantly different average values and within test groups as indicated by the high coefficients of variation (CV) obtained. The initial modulus values obtained for the Kevlar 49 fibers do not exhibit a wide variation as indicated by the fairly low CV. The rupture tenacity and elongation are more variable, however, showing CV's greater than 10% at both 1.0 and 5.0 inch gauge lengths.

Both fibers show a modest gauge length effect: the rupture tenacity and elongation both decrease as the gauge length increases, indicating some degree of flaw-dependent behavior. The data obtained at a 5.0 inch gauge length will be used subsequently for comparison with yarn properties.

Kevlar 29 exhibits approximately the same rupture tenacity as Kevlar 49, almost twice the rupture elongation and half the initial modulus. Average stress-strain diagrams of the two materials based on the 5.0 inch gauge length tests are presented in Figure 17.

5. Bending Modulus of Kevlar Fibers

The bending modulus of Kevlar 29 and Kevlar 49 fibers was determined using the Searle double pendulum apparatus [1]. The values obtained are given in Table 13 which shows that the bending modulus is somewhat lower than the observed fiber tensile modulus in both cases. The results for Kevlar 29 show a wider variation than those for the Kevlar 49 as was the case with the tensile modulus measurements.

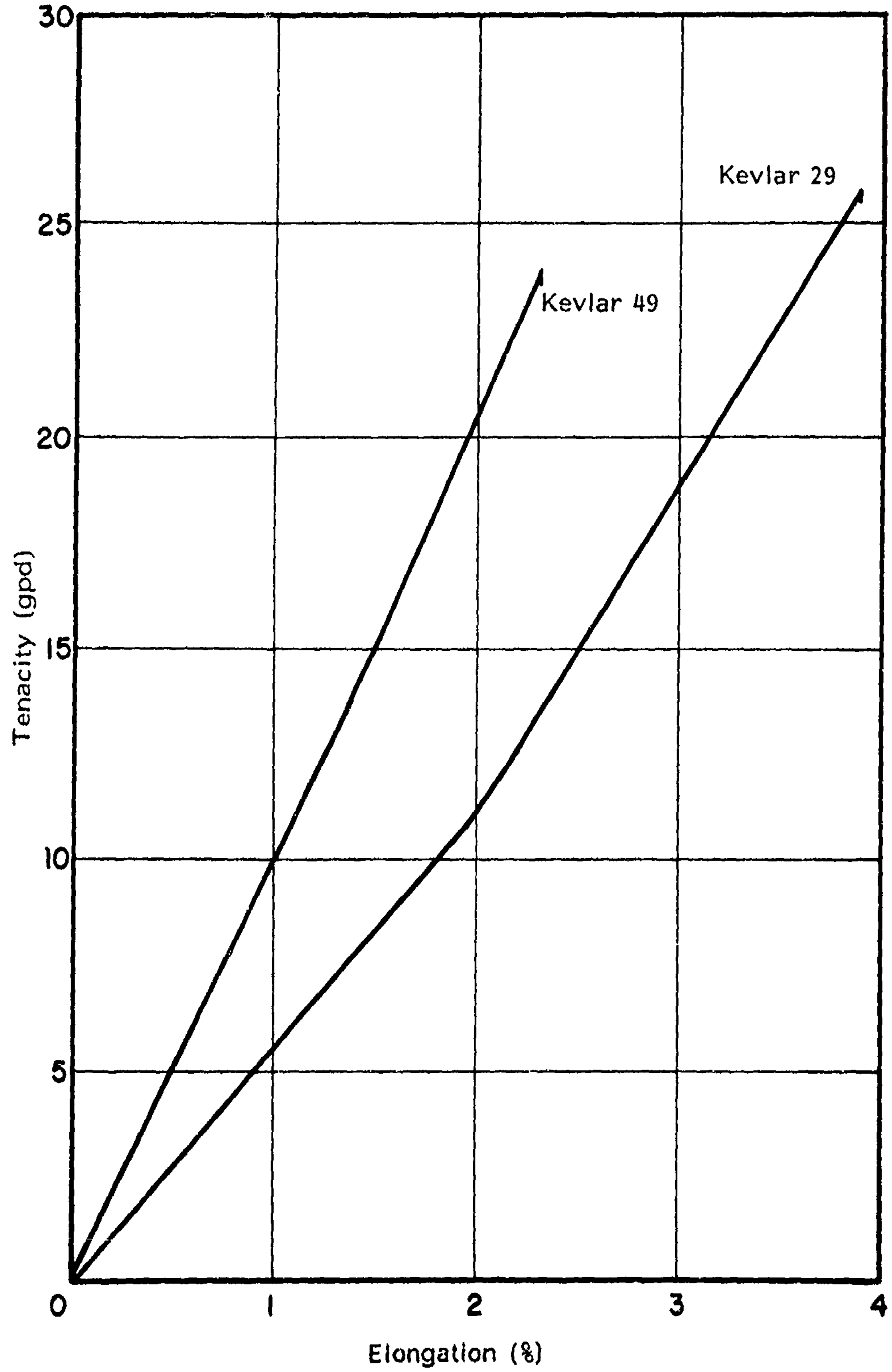

Figure 17. Average Stress-Strain Diagrams of Kevlar Fibers

TABLE 13

BENDING MODULUS OF KEVLAR FIBERS
Searle Double Pendulum Method

Material		Bending Modulus (gpd)	Initial Tensile Modulus (gpd)	Calculated Axial Compressive Modulus (gpd)
Kevlar 29		393		
		591		
		345		
	Avg	413 (7.7)	546 (10.1)	319 (5.9)
Kevlar 49		862		
		808		
		787		
	Avg	822 (15.3)	989 (18.4)	603 (11.2)

The numbers in parentheses give the modulus in 10^6 psi units.

The axial compressive modulus can be calculated from the ratio of bending to tensile modulus using a relationship derived by Freeston [2] which assumes displacement of the neutral axis during bending. These calculated values are also given in Table 13 and show an axial compressive modulus approximately 60% of the tensile modulus.

6. Dynamic Modulus of Kevlar and PBI Fibers

The dynamic modulus [3] of Kevlar 29, Kevlar 49, PRD-49 IV, and PBI was measured on a Pulse Propagation Meter* under a nominal tension of 1/2 gpd. The values obtained are given in Table 14. Comparison data for nylon and Nomex are also included [4].

Usually, the greater the degree of crystalline alignment of the material being measured, the more closely the dynamic and static modulus measurements agree. As expected, the ratio of dynamic to static modulus for the Kevlars and the PRD-49 IV are much lower than those for nylon and Nomex. The ratio for PBI, however, is surprisingly low for a material not regarded as particularly crystalline.

*Manufactured by H. M. Morgan Co., Inc., Cambridge, Massachusetts.

TABLE 14

DYNAMIC MODULUS OF KEVLAR AND PBI

Material		Dynamic Modulus (gpd)	Static Modulus (gpd)	Ratio Dynamic/ Static Modulus
Kevlar 29		743		
		743		
		729		
	Avg	738 (13.7)	546* (10.1)	1.35
Kevlar 49		1121		
		1121		
		1054		
	Avg	1049 (19.5)	989* (18.4)	1.11
PRD-49 IV		930		
		917		
		910		
	Avg	919 (17.1)	746** (13.8)	1.23
PBI		172		
		165		
		167		
	Avg	168 (3.1)	126** (2.3)	1.33
Nylon		88 (1.6)	44** (0.8)	2.00
Nomex		181 (3.4)	113** (2.1)	1.60

*Fiber modulus.
**Untwisted yarn modulus: fiber data not available.
The numbers in parentheses give the modulus in 10^6 psi units.

SECTION V

TWISTED KEVLAR YARNS

1. Tensile Properties of Twisted Kevlar Yarns

The effect of twist on the tensile properties of high modulus, low elongation yarns may be expected to be greater than on yarns having more usual textile properties. Since high twist levels might be desirable in some textile structures, it was decided to study the effect of twist on some of the properties of Kevlar 29 and Kevlar 49 yarns.

Because the Kevlar 29 being studied is approximately 1000 denier and the Kevlar 49 only 400 denier, comparisons of yarns twisted to the same surface helix angle are more appropriate than for those twisted the same number of turns per inch twist. Accordingly, small quantities of yarn were twisted on a standard twisting frame to twist levels corresponding to estimated surface helix angles of 10°, 20°, and 30°. In fact, the resulting twisted yarns resembled ribbon twisted structures rather than the ideal helically twisted structure often assumed in analyses of yarn behavior. It is not as yet certain whether the ribbon twisting is the result of the flattened form of the untwisted yarn or of the high modulus, low elongation properties of the fiber which would tend to prohibit the large length differentials between filaments inherent in the helically twisted structure.

The tensile properties of these yarns were determined at a strain rate of 0.167%/sec (10%/min) using the 1.0 inch diameter capstan jaws described in Section II - 2. With this jaw system, the nominal specimen length is equivalent to twice the nominal gauge length. A summary of the properties determined with a 20 inch specimen length are given in Table 15, actual twist and denier values are also tabulated. Individual data may be found in Table 25 of the Appendix. The effect of twist on yarn rupture tenacity is plotted in Figure 18; of twist on initial modulus in Figure 19. Typical stress-strain diagrams of the twisted yarns are presented in Figures 20 and 21.

The data show a large decrease in tenacity for the untwisted yarn bundle for both Kevlar materials based on the strength of individual fibers. The bundle efficiency of the untwisted Kevlar 29 yarn is only 82%; that of the Kevlar 49, 79%. These low values may be due to several factors: a) the influence of variation in fiber properties; b) the possibility of compressive damage due to crossing fibers on the snubbing surfaces of the capstan jaws; and c) unequal loading of the filaments in the yarn bundle resulting from differences in filament length within the bundles. These length differences are undoubtedly small but their effect, combined with a variation in fiber properties, can be disastrous where low-elongation materials are concerned. The greater strength of both the Kevlar 29 and Kevlar 49 yarns twisted to a nominal surface helix angle of 10° tends to confirm the effect of length differentials in the untwisted yarn bundle since such differentials would tend to be somewhat equalized in a slightly twisted structure.

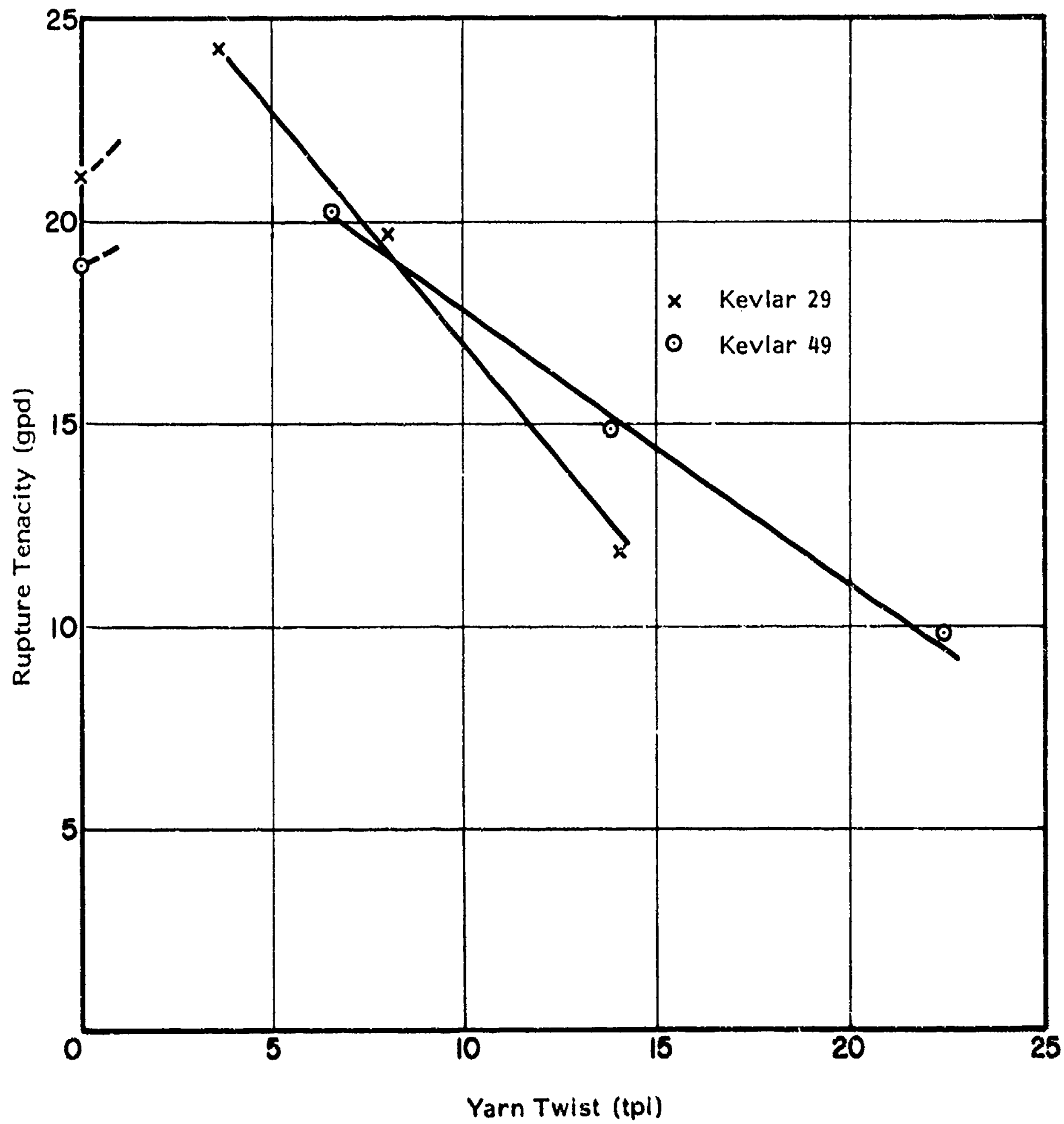

Figure 18. Effect of Twist on Rupture Tenacity of Kevlar Yarns

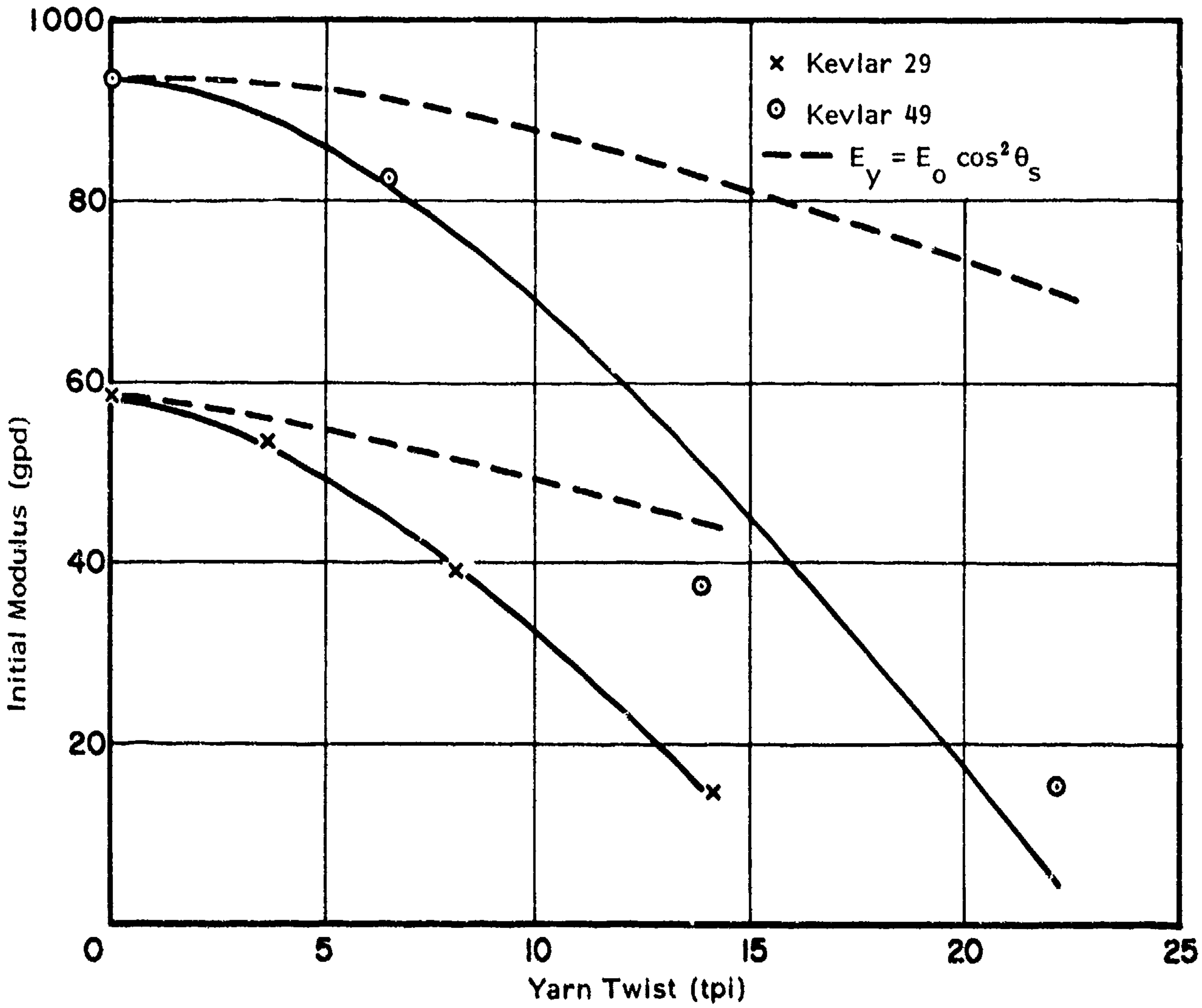

Figure 19. Effect of Twist on Initial Modulus of Kevlar Yarns

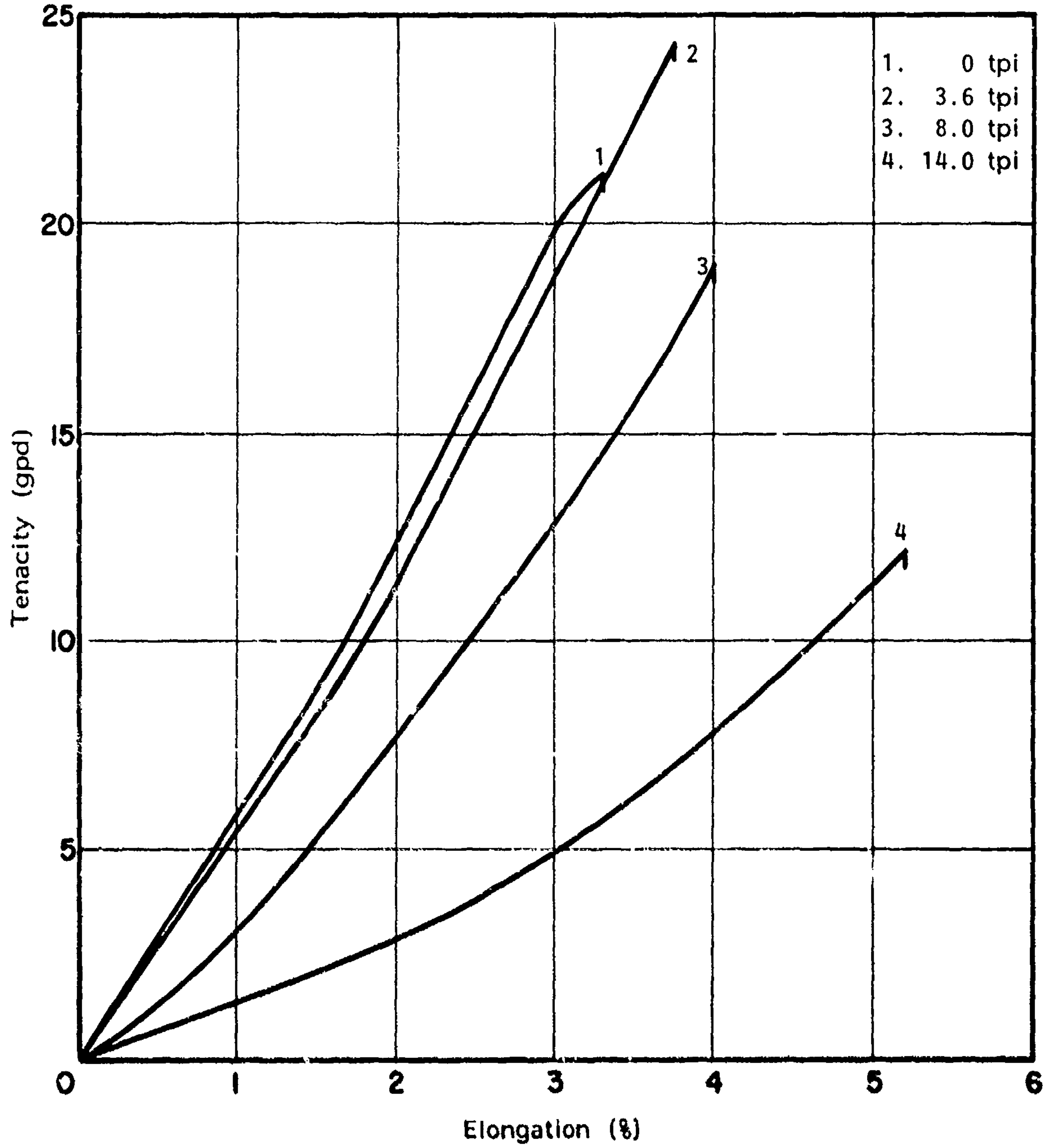

Figure 20. Typical Stress-Strain Diagrams of Kevlar 29 Twisted Yarn

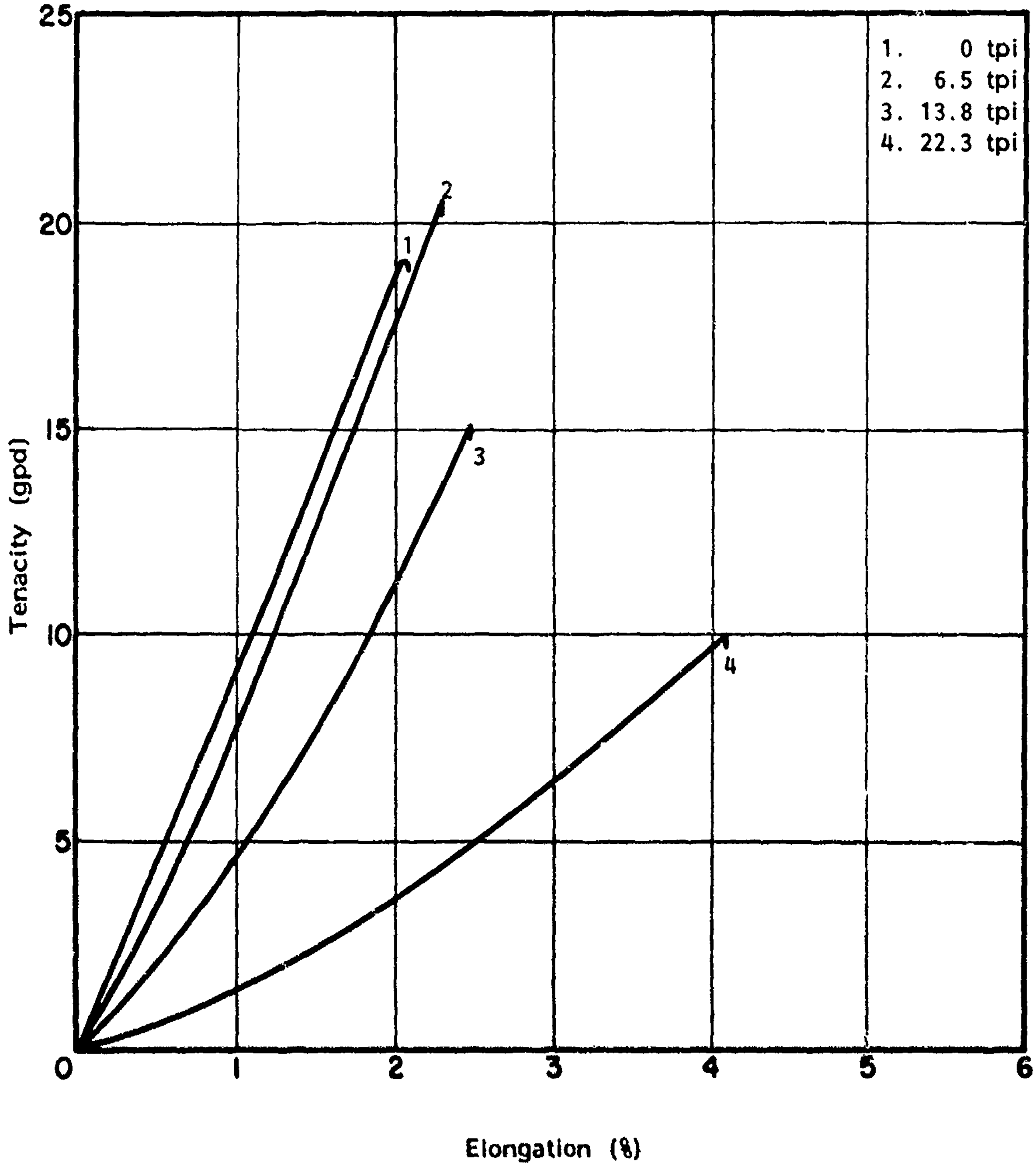

Figure 21. Typical Stress-Strain Diagrams of Kevlar 49 Twisted Yarn

TABLE 15

TENSILE PROPERTIES OF TWISTED KEVLAR YARNS
(20-inch specimen length)

Material	Estimated Surface Helix Angle* (°)	Yarn Twist (tpi)	Denier	Initial Modulus (gpd)	Rupture Elong (%)	Rupture Tenacity (gpd)	Strength Change (%) **	***
Kevlar 29	0	0	1057	587 (10.9)	3.2	21.1 (392)	-18	---
	10	3.6	1072	539 (10.0)	3.8	24.3 (451)	- 5	+15
	20	8.0	1117	387 (7.2)	4.0	19.7 (366)	-23	- 7
	30	14.0	1185	149 (2.8)	5.2	11.9 (221)	-54	-44
Kevlar 49	0	0	405	938 (17.4)	2.0	18.9 (351)	-21	---
	10	6.5	406	828 (15.4)	2.2	20.3 (377)	-15	+ 7
	20	13.8	432	375 (7.0)	2.6	14.8 (275)	-38	-22
	30	22.3	458	154 (2.9)	4.1	9.8 (182)	-59	-48

*Based on a helically twisted model structure.
**Based on individual fiber strength.
***Based on the strength of the untwisted yarn.
The numbers in parentheses give the modulus in 10^6 psi units or the rupture stress in 10^3 psi units.

Neither the drastic decrease in tenacity with twist after the initial increase at the lowest twist level nor the large decreases in initial modulus throughout the range of twists illustrated in Figures 18 and 19 can be explained on the basis of a simple yarn model taking into account only geometrical changes in yarn structure with twist. The dashed line in Figure 19 represents the initial modulus predicted by the use of the expression $E_y = E_0 \cos^2\theta$ where E_y and E_0 are the twisted and untwisted yarn moduli respectively and θ_s is the surface helix angle of the yarns [5]. This expression is derived from an ideal model of a helically twisted structure. The actual moduli of the Kevlar yarns fall off much more rapidly with twist than this simple model predicts. The fact that the real structure is more like a twisted ribbon than a helically twisted structure would imply that the fall-off of modulus with twist should be faster than predicted by the $\cos^2\theta$ law. However, the actual structure has not yet been analyzed in sufficient detail to allow a more reliable model to be set up.

In an effort to attribute these large changes in tenacity and initial modulus to other than geometrical factors arising from the twisted state tensile properties of the following were investigated: fibers removed from twisted yarns; twisted fibers; fibers previously bent; laterally compressed fibers.

a. Effect of Twist on the Tensile Properties of Kevlar Filaments

In order to determine to what extent the loss in strength of the twisted yarns was due to filament damage, tensile tests were performed on single filaments

removed from the twisted yarns. These filaments were mounted on cardboard tabs with epoxy cement and tested using a 5.0 inch gauge length and 0.167%/sec (10%/min) strain rate. The tensile properties given in Table 15 and Table 25 of the Appendix, and the rupture tenacity plotted as a function of yarn twist in Figure 22 show loss of fiber strength increasing with yarn twist, becoming quite severe at the highest twist levels: up to 25% for Kevlar 29 and 32% for Kevlar 49. This loss in strength of individual filaments within the twisted yarn structures accounts for roughly one-half of the yarn strength loss observed at the highest twist levels based on the original fiber strength. In addition, the data in Table 16 show a decrease in fiber modulus with increasing yarn twist suggesting that some permanent disorientation of the fiber molecular structure occurs as the result of yarn twisting.

Further tests were carried out to determine if the insertion of twist alone into a single filament on the order of the amount of twist imposed on the yarns was sufficient to cause significant loss in strength and decrease in modulus. Single filaments of Kevlar 29, 5.0 inches long, were twisted to levels of 8 and 14 tpi and then tensile tested. The results, summarized in Table 17 and given individually in Table 27 of the Appendix, show no significant change in any of the fiber tensile properties with imposed twist. Therefore, it does not appear that the fibers removed from the twisted yarns were damaged by twist alone.

TABLE 16

TENSILE PROPERTIES OF FIBERS REMOVED FROM TWISTED YARNS
(5.0 inch gauge length)

Material	Yarn Twist (tpi)	Initial Modulus (gpd)	Ruptur Elongation (%)	Rupture Tenacity (gpd)	Strength Change (%)
Kevlar 29	0	546 (10.1)	3.9	25.6 (475)	---
	3.6	555 (10.3)	3.7	23.9 (444)	- 7
	8.0	514 (9.5)	3.7	22.1 (410)	-14
	14.0	523 (9.7)	3.2	19.3 (358)	-25
Kevlar 49	0	989 (18.4)	2.3	23.8 (442)	---
	6.5	959 (17.8)	2.2	22.6 (419)	- 5
	13.8	931 (17.3)	1.9	18.8 (349)	-21
	22.3	913 (16.9)	1.7	16.3 (303)	-32

TABLE 17

TENSILE PROPERTIES OF TWISTED KEVLAR 29 FIBERS
(5.0 inch gauge length)

Twist (tpi)	Initial Modulus (gpd)	Rupture Elongation (%)	Rupture Tenacity (gpd)
0	546 (10.1)	3.9	25.6 (475)
8	552 (10.2)	3.8	25.8 (479)
14	566 (10.5)	3.8	25.8 (479)

The numbers in parentheses give the modulus in 10^6 psi units or the rupture stress in 10^3 psi units.

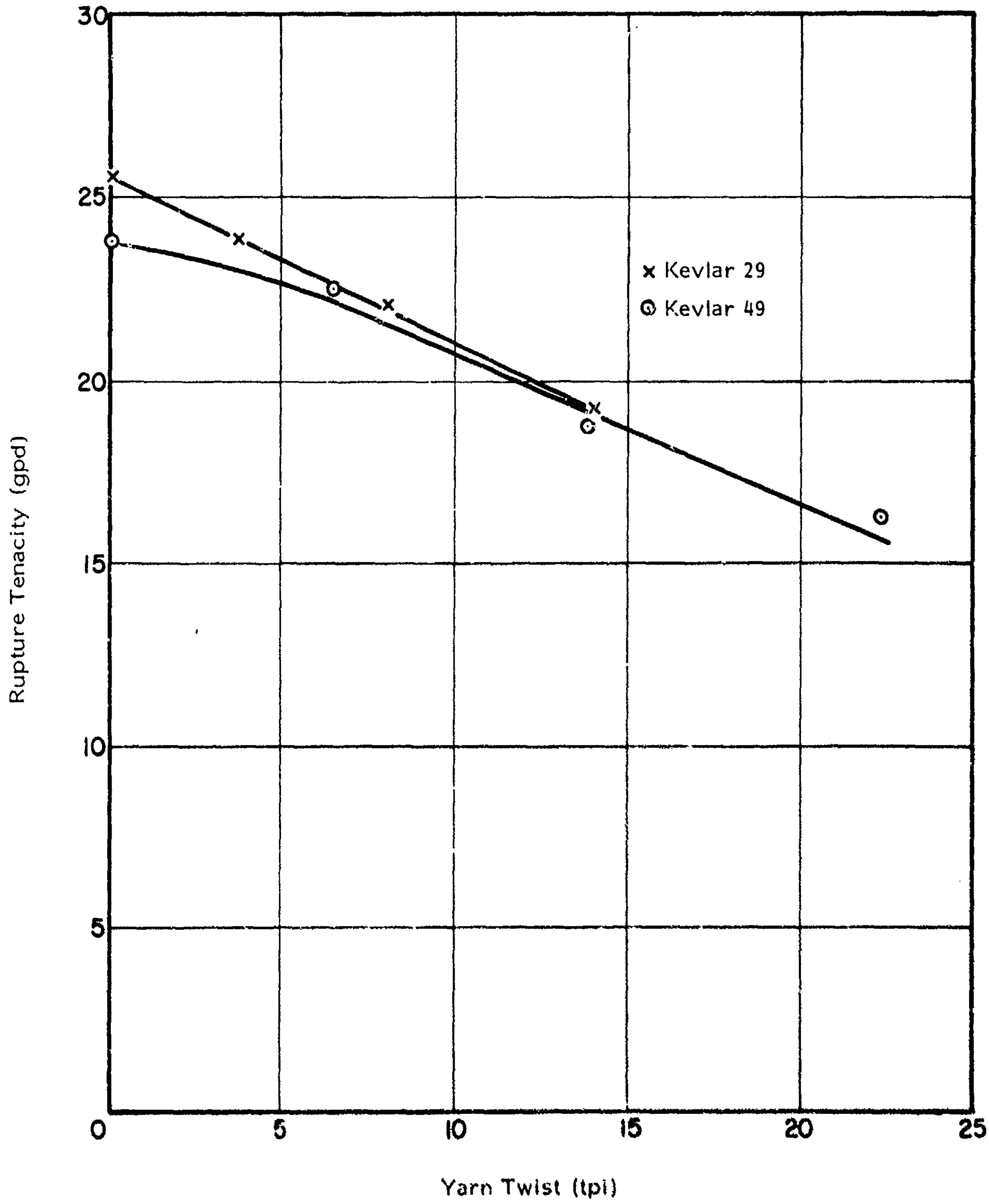

Figure 22. Strength of Filaments Removed from Twisted Kevlar Yarns

b. Effect of Bending History on the Tensile Properties of Kevlar 49 Filaments

In order to determine to what extent bending alone is responsible for the degradation noted in Kevlar fibers removed from twisted yarns, Kevlar 49 fibers taken from untwisted yarns were bent to various degrees, straightened and tensile tested. The bending was imposed by wrapping the filaments around mandrels chosen so that their diameters corresponded roughly with the maximum theoretical curvature of fibers in yarns twisted to 10, 20 and 30° surface helix angles. The mandrel diameters used and the data obtained are summarized in Table 18, and given individually in Table 28 of the Appendix. (Equivalent maximum bending strains, ε_b, are also noted.) Since the diameter of the traveller over which the yarn passes on the twisting frame is on the order of 0.15 inch, mandrel diameters of 0.086 and 0.040 inch, equivalent to surface helix angles of 20 and 30°, are sufficiently small to show any additional effects of bending arising from the twisted yarn geometry.

TABLE 18

TENSILE PROPERTIES OF PREVIOUSLY BENT KEVLAR 49 FIBERS
(1.0 inch gauge length)

Mandrel Diameter (inches)	Initial Modulus (gpd)	Rupture Elongation (%)	Rupture Tenacity (gpd)	Strength Change (%)
0	989 (18.4)	2.7	26.2 (486)	---
0.33 (ε = 0.14%)	974 (18.1)	2.5	24.4 (453)	-7
0.086 (ε = 0.54%)	992 (18.4)	2.5	24.9 (462)	-5
0.040 (ε = 1.16%)	960 (17.8)	2.5	24.0 (445)	-8

The numbers in parentheses give the modulus in 10^6 psi units, on the rupture stress in 10^3 psi units.

The fibers were tested at 0.167%/sec (10%/min) strain rate using a 1.0 inch gauge length. The data in Table 18 shows only small losses in strength suffered by the previously bent filaments and only a small decrease in modulus at the highest twist; correlation with degree of bending is not marked. It is thus apparent that bending imposed during twisting is not by itself responsible for the 20-30% strength losses previously reported for Kevlar 49 filaments removed from twisted yarns nor for the 6-8% decrease in initial modulus.

c. Effects of Transverse Compression on the Strength of Kevlar Fibers

Since individual filaments in twisted yarns under tension must suffer an appreciable degree of transverse compression, experiments were performed

to determine if degradation in strength of Kevlar 29 and Kevlar 49 fibers is caused by transverse compression. Also tested was 2 denier nylon fiber for comparison. The test apparatus consisted of two, optically flat, parallel steel platens mounted in an Instron. Fibers were aligned unidirectionally between the platens and compressed at the rate of 0.02 inch/min to a preset load value. The specimens were then tensile tested in the same manner as described in Section IV-4 using a 1.0 inch gauge length.

Transverse loads of 18 lb and 110 lb per fiber linear inch were imposed on the fibers over a length of approximately 0.45 inch. The transition regions between compressed and uncompressed fiber involved very gradual changes in geometry, thus reducing the possibility of stress concentrations. The Kevlar fibers appeared to undergo plastic yielding upon compression but retained integrity surprisingly well with only slight fibrillation. The nylon fibers also exhibited a yield in compression. The fiber cross-sectional aspect ratios averaged ~5:1 after 18 lb/inch compressive loading and ~12:1 after 110 lb/inch. Elastic indentation of the platens by the fibers at such high transverse loadings was likely, however, so that some of the load may have been borne by contacting platens and the true loads on each fiber specimen were possibly less than those stated.

The results of the tensile tests performed on the compressed fibers are summarized in Table 19; individual test results are given in Table 29 in the Appendix. The compressed Kevlar fibers lost 11-15% of their strength at 18 lb/inch and 22-25% at 110 lb/inch. Although no estimate of compressive forces acting in a twisted yarn are available, the higher load level of 110 lb/linear inch is thought to be extremely high. Thus, it is unlikely that fibers in a highly twisted yarn even under tension would lose more than 10-15% of their strength due to transverse compression. The nylon fibers suffered a lesser degree of strength degradation in compression than the Kevlar fibers.

An exact measure of the modulus of the compressed fibers cannot be obtained from the stress-strain curves because the fibers were deformed over only about half of their length. However, an estimate of the percentage decrease in modulus with increasing compressive load can be made for the Kevlar fibers by dividing the maximum stress by the maximum strain since the compression curves are approximately linear. This estimate, also included in Table 19, shows a significant decrease in the modulus of both Kevlar materials even at the lower load level.

d. Summary

The large decreases in tenacity shown by the highly twisted Kevlar yarns can be partially accounted for by loss in filament strength. The remainder of the strength loss can probably be explained by the combined effects of geometrical changes in the yarn structure caused by twisting, statistical variation in fiber properties, and length variations in the untwisted bundle. Platt et al [6] have calculated values of strength loss with

TABLE 19

TENSILE PROPERTIES OF TRANSVERSELY COMPRESSED KEVLAR FIBERS

Material	Transverse Load (lbs/inch)	Estimated Modulus Change (%)	Rupture Strain (%)	Rupture Tenacity (gpd)	Strength Change (%)
Kevlar 29	0	---	4.0	23.2 (431)*	---
	18	-15	4.2	20.7 (384)	-11
	110	-20	3.9	18.0 (334)	-22
Kevlar 49	0	---	2.7	27.8 (516)	---
	18	- 8	2.5	23.7 (440)	-15
	110	-25	2.7	20.8 (386)	-25
Nylon	0	---	29	6.48 (120)	---
	18	---	21	6.09 (113)	- 6
	110	---	21	5.59 (104)	-14

twist for an ideal, helically twisted yarn structure and a normal distribution of fiber strengths; these approximate predictions appropriate for the Kevlar yarns are given in Table 20, column 3, for comparison with the measured losses, column 1. As shown in this table, the strength losses of fibers removed from the twisted yarns, column 2, when added to the losses predicted by Platt, approximate the actual strength losses sufficiently to illustrate the advisability of a statistical approach. Attempts will be made in the coming months to refine such an approach perhaps assuming a Weibull rather than normal distribution of fiber properties and including the effects of filament length variations. It is hoped that the large decreases in yarn modulus with twist can also be explained as a part of this analysis.

Perhaps of more importance than the decrease in yarn rupture tenacity and modulus with twist are the large losses in the strength of filaments removed from the twisted yarns. These losses cannot be fully explained by the individual effects of torsion, bending and transverse compression. These three types of deformation when imposed simultaneously on a Kevlar fiber as in a twisted yarn, apparently exert a greater adverse effect on the fiber strength than each acting singly. However, it does appear that transverse compression is capable of most seriously altering the fiber properties. An understanding of the nature or origin of the damage to the fibers by these types of deformation has a greater range of applicability than to twisted structures alone, especially since it appears that torsion plays the least important role. Kevlar yarns incorporated into textile structures of any kind are likely to be subject to various degrees of bending and lateral compression, and presumably will suffer the same kind of degradation as in a highly twisted yarn structure. Attempts will be made in the coming months to further describe the nature of fiber degradation resulting from bending and lateral compression.

The numbers in parentheses give the rupture stress in 10^3 psi units.

TABLE 20

STATISTICALLY PREDICTED YARN STRENGTH LOSSES
COMPARED TO MEASURED LOSSES

Material	Yarn Twist (tpi)	1 Measured Yarn Strength Loss* (%)	2 Measured Fiber Strength Loss (%)	3 Predicted Yarn Strength Loss** (%)	4 Total, 2 + 3 (%)
Kevlar 29	0	-18	---	~-10	-10
	3.6	- 5	- 7	~-12	-17
	8.0	-23	-14	~-20	-34
	14.0	-54	-25	~-30	-55
Kevlar 49	0	-21	---	~-20	-20
	6.5	-15	- 5	~-22	-27
	13.8	-38	-21	~-21	-46
	22.3	-59	-32	~-36	-68

*On the basis of average original fiber strength.
**Assuming no fiber strength losses in the twisted structure.

2. Effect of Specimen Length on the Rupture Tenacity of Twisted Kevlar Yarns

During the course of tensile testing the twisted Kevlar yarns, the influence of specimen length on the measured ruptured tenacity was investigated. The results are presented graphically in Figures 23 and 24 which also include the rupture tenacity of single fibers tested at different gauge lengths. As mentioned previously, the specimen length used in the yarn testing is twice the stated gauge length.

The specimen length effect on rupture tenacity is not insignificant: 5-10% loss in strength for the fibers over a length of 1 to 5 inches; 5-10% loss in strength for the yarns over a length of 10-30 inches, with the exception of Kevlar 29 at the lowest twist level. The loss in strength of the fibers with increasing specimen length is probably the result of flaw-dependent failure. However, the loss in strength of the yarns with increasing length probably also reflects the increased probability that a longer length of yarn includes a greater degree of filament length variation.

The tenacity, in general, decreases linearly with increasing specimen length over the lengths tested. This is disturbing since the anticipated end-use structures of Kevlar such as braids and webbings are likely to be employed in long lengths. The specimen length at which the tenacity of the yarns ceases to decrease should be determined; or, alternately, the

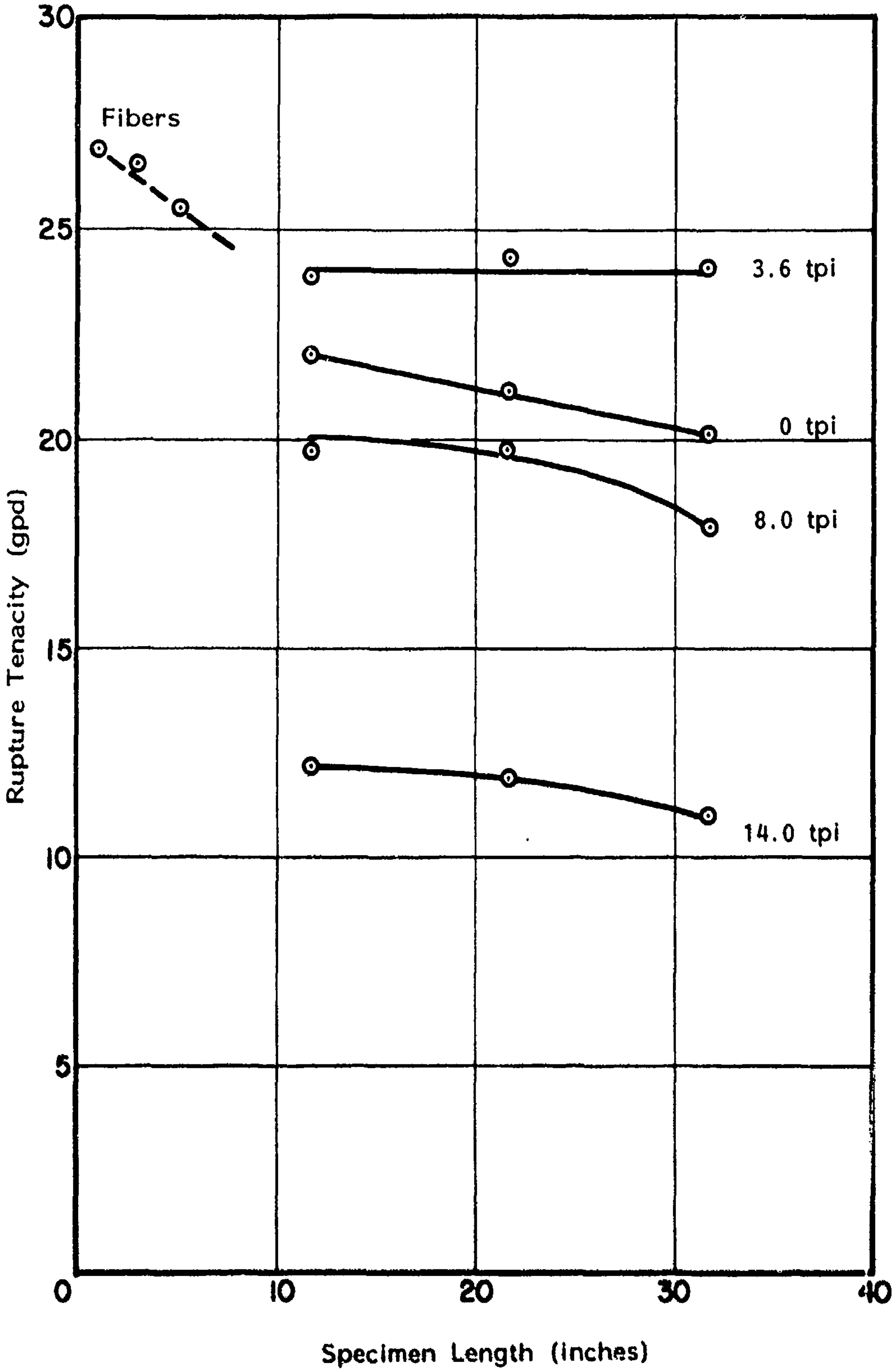

Figure 23. Effect of Specimen Length on Rupture Tenacity of Kevlar 29 Yarn

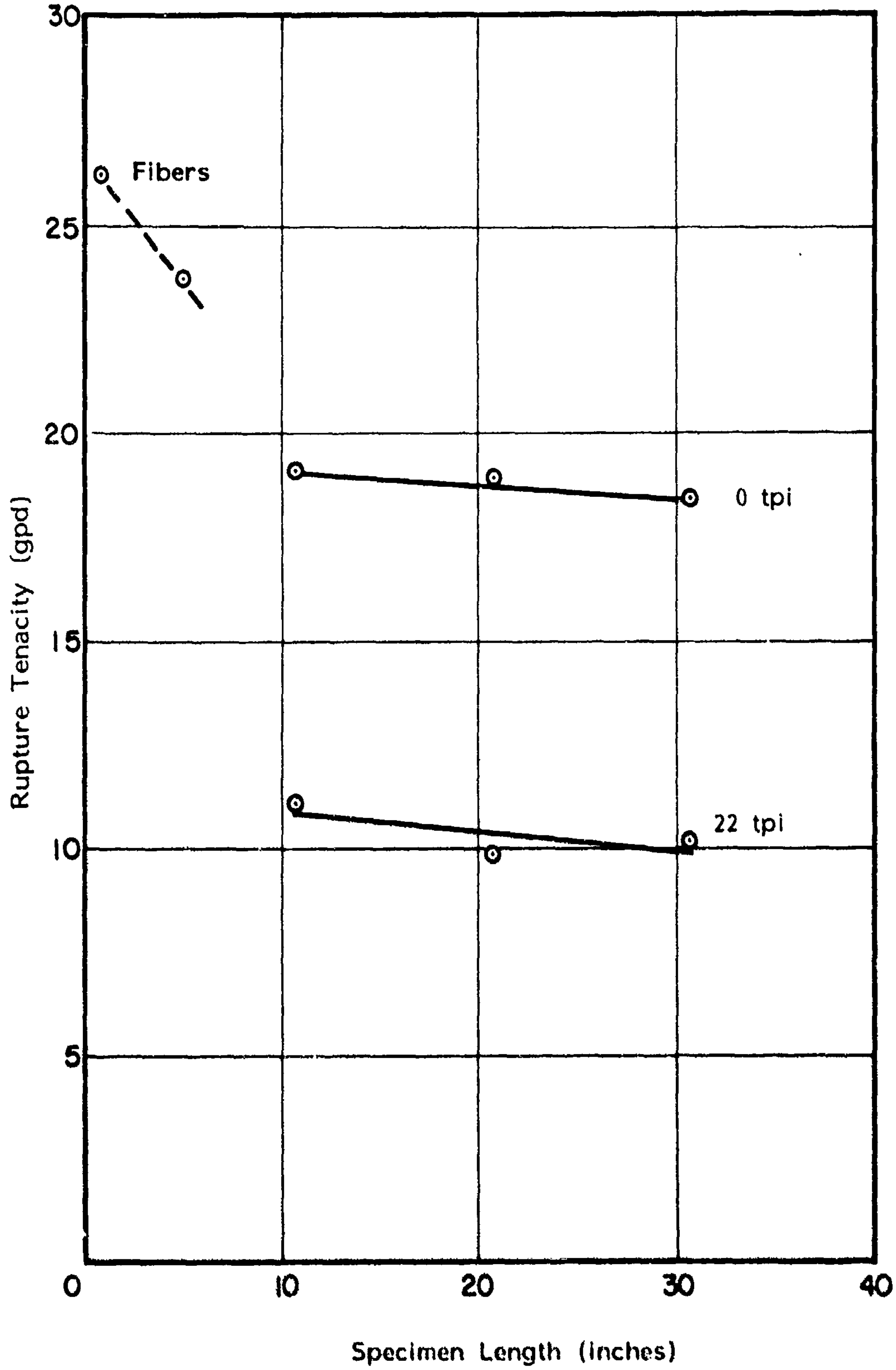

Figure 24. Effect of Specimen Length on Rupture Tenacity of Kevlar 49 Yarn

existence of a preferred twist level should be confirmed at which the gauge length effect is minimized, as suggested by the flat curve for Kevlar 29 twisted 3.6 tpi.

3. Loop and Knot Strength of Kevlar Yarns

The loop strength of Kevlar 29 and Kevlar 49 yarns was measured in the usual way by interlocking two pieces of yarn as suggested in ASTM Test Method D2256. The knot strength was measured by tying a simple overhand knot in a test specimen. Both sets of tests were performed using the 1.0 inch diameter capstan jaws described in Section II-2. A strain rate of 0.167%/sec (10%/min) was employed with a gauge length of 10 inches.

The resulting knot and loop strengths are reported in Table 21 and Tables 30 and 31 of the Appendix. The loop and knot strengths are plotted in Figures 25 and 26 with unlooped, unknotted yarn tenacities for comparison; the loop and knot efficiencies based on the strength of the corresponding twisted but unlooped or unknotted yarn are plotted in Figures 27 and 28.

TABLE 21

LOOP AND KNOT STRENGTH OF TWISTED KEVLAR YARNS

Material	Yarn Twist (tpi)	Loop Strength (gpd)	Loop Efficiency (%)	Knot Strength (gpd)	Knot Efficiency (%)
Kevlar 29	0	13.6	64	8.5	40
	3.6	12.6	52	7.6	31
	8.0	11.9	60	9.6	49
	14.0	8.5	71	7.6	64
Kevlar 49	0	10.7	57	7.4	39
	6.5	7.8	38	7.7	38
	13.8	7.4	50	8.2	55
	22.3	6.9	70	6.3	64

The loop strength and efficiency of the yarns is in general higher than the knot strength and efficiency. The difference is greatest for the untwisted yarns probably because the untwisted yarn can flatten more in the looped configuration than in the knot configuration minimizing bending curvature and length differentials. Both the loop and knot efficiencies show an upward trend after an initial decrease at the lowest twist level; this trend reflects the fact, illustrated in Figure 25 and 26, that the strength of the twisted yarn decreases more rapidly with twist than the strength of either the knotted or looped twisted yarn.

It is interesting to note in Figures 25 and 26 that the tensile knot and loop strength curves of the twisted yarns can be extrapolated to a somewhat common

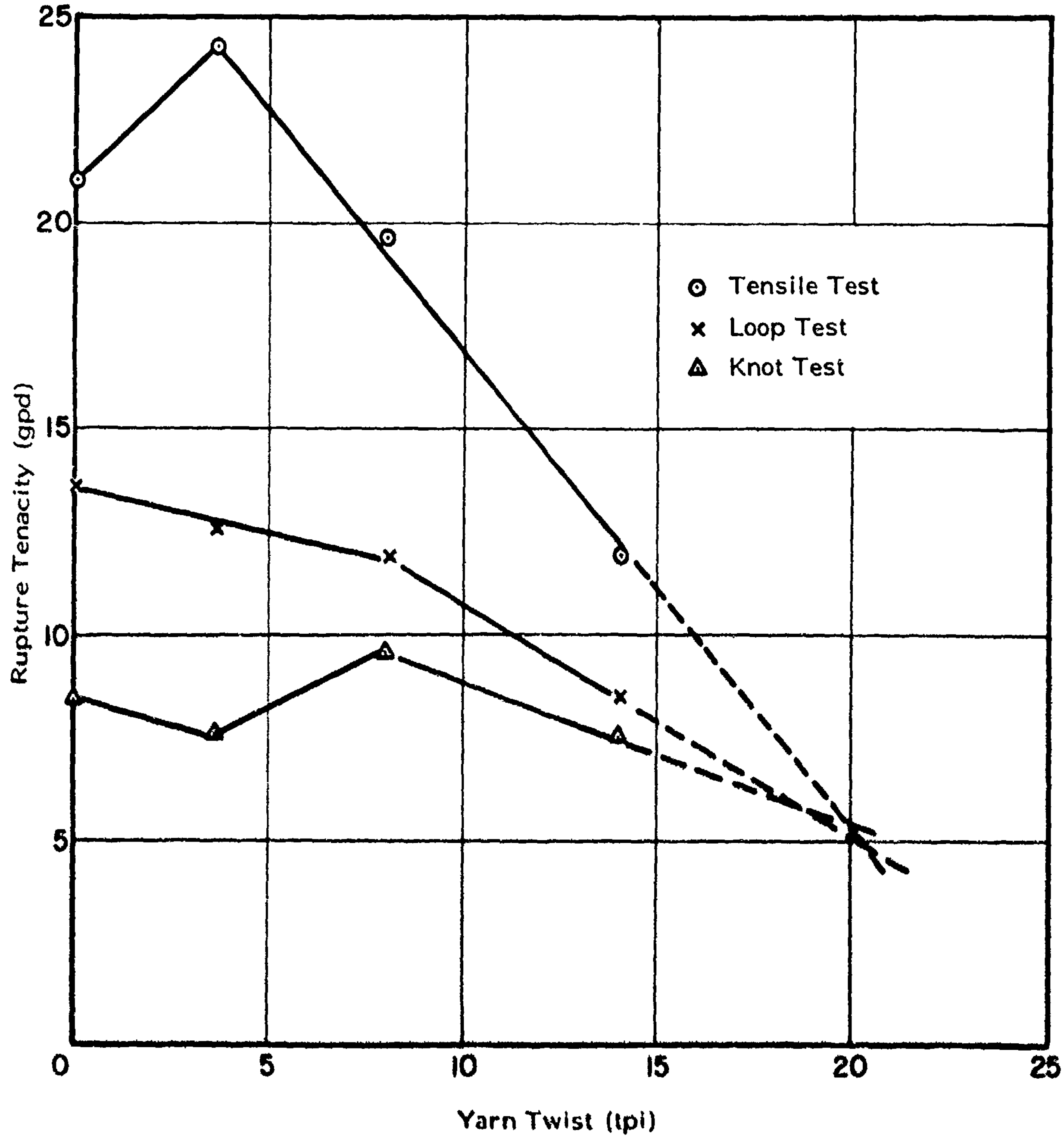

Figure 25. Loop and Knot Strength of Twisted Kevlar 29 Yarn

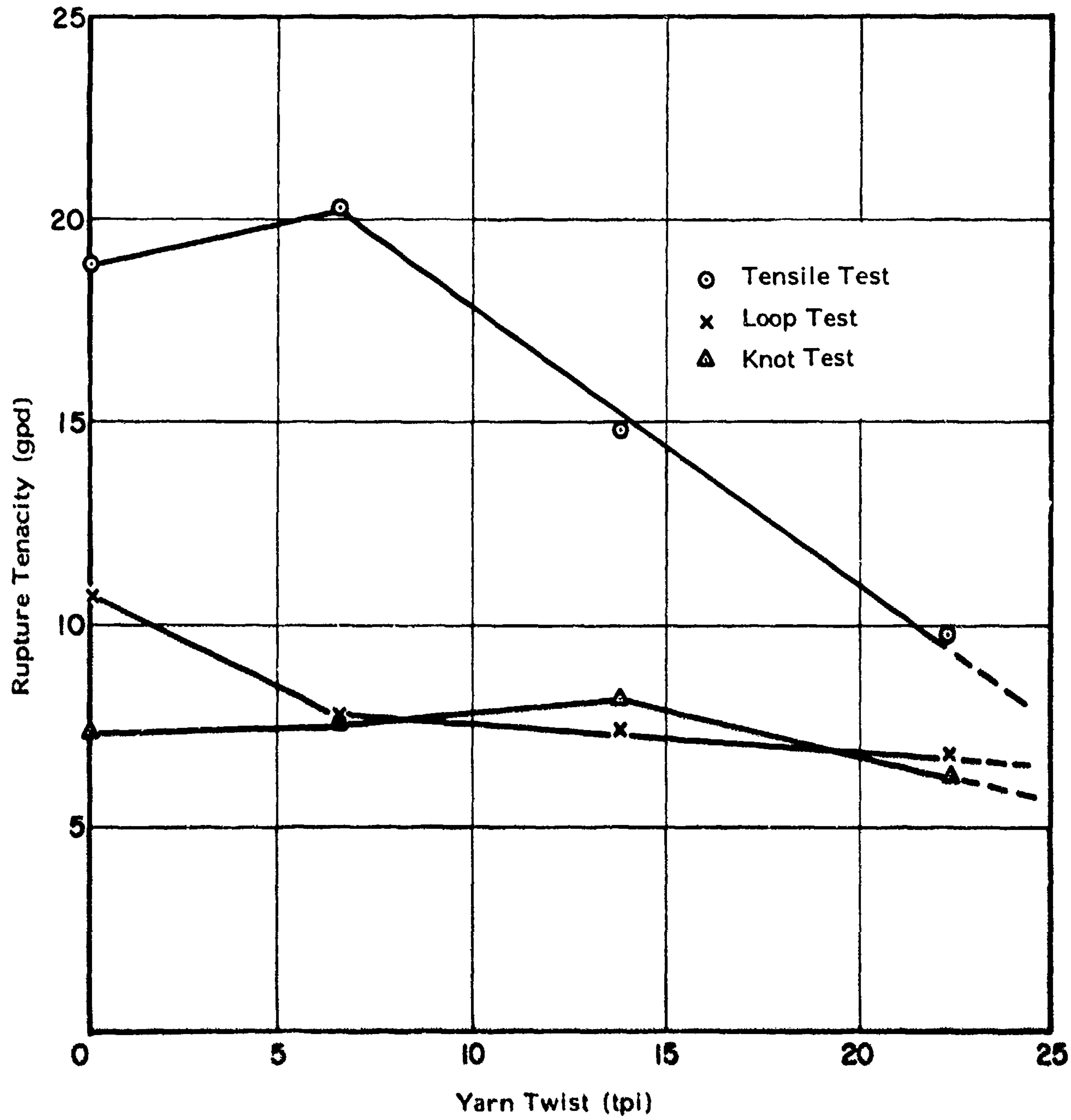

Figure 26. Loop and Knot Strength of Twisted Kevlar 49 Yarn

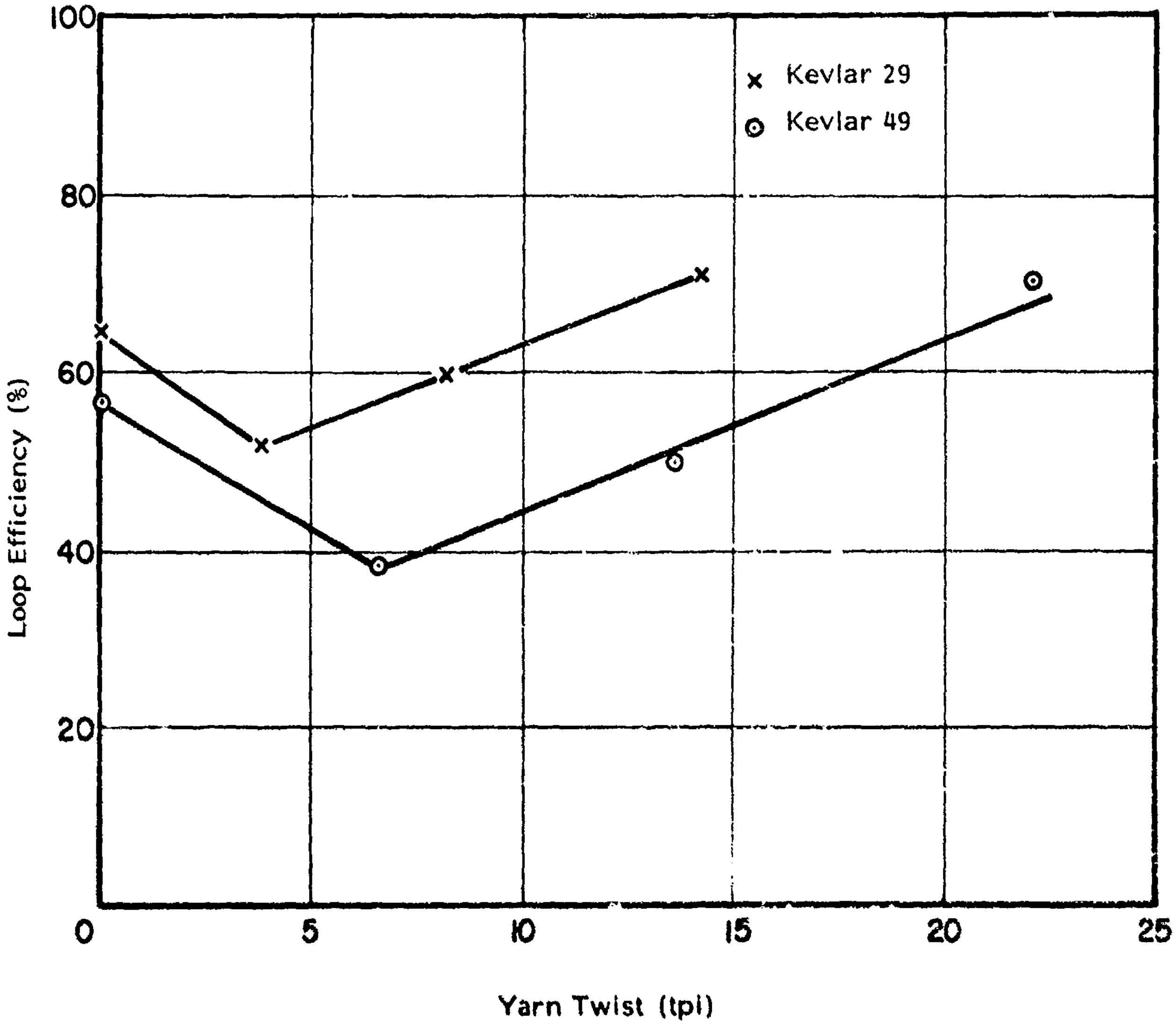

Figure 27. Loop Efficiency of Twisted Kevlar Yarns

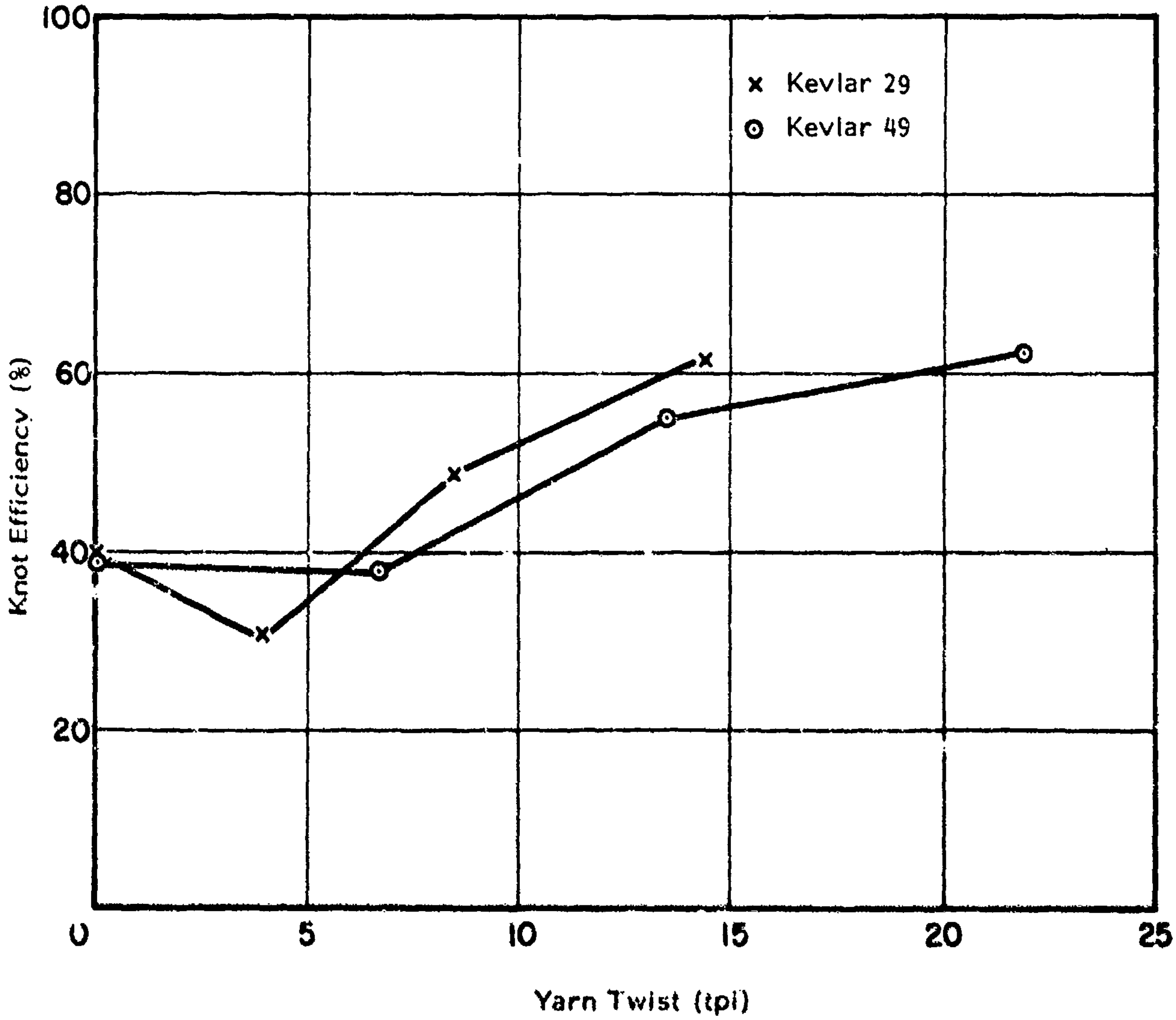

Figure 28. Knot Efficiency of Twisted Kevlar Yarns

value of twist not too much greater than the highest tested: about 19-21 tpi for the Kevlar 29 and 27-29 tpi for the Kevlar 49. At this value of twist presumably the loop or knot would impose no greater degree of damage than occurs in the twisted yarn and efficiencies would approach 100%. In fact, a simplified analysis of the curvatures in the knot and loop compared with filament curvature in a twisted yarn show that at a surface helix angle of 45°, the average yarn curvature imposed by the knot or loop equals the filament curvature imposed by twisting*. The twist levels corresponding to a surface helix angle of 45° are ~20 tpi for the Kevlar 29 and ~32 tpi for the Kevlar 49, values in good agreement with the extrapolated points.

Bending curvatures imposed by the knot or loop on the twisted yarn are equivalent; transverse pressure arising in the knot or loop region are probably also of the same magnitude. However, the length of yarn involved in the knot is greater than that in the loop; hence the presence of the knot probably creates greater length differentials in the total length of yarn being tested than the presence of the loop. Perhaps this accounts for the generally lower knot strength than loop strength.

Conclusions

Kevlar 29 and Kevlar 49 yarns have remarkable and unique properties which make them of particular interest to the Air Force. Their high rupture tenacities offer the potential of significant weight saving over nylon, for example, in fabrics having the same strength. Additional study is contemplated of other properties such as torque-twist-recovery characteristics and bending recovery, in order to provide the data needed for design of optimum structures of a variety of types. In addition, failure mechanisms will be studied to obtain an understanding of some of the unusual aspects of the behavior of these yarns, some of which have been described in this report.

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*(The curvature of fibers in a twisted yarn, K_1, is related to the surface helix angle as follows:

$$K_1 = \frac{\sin^2 \theta}{R}$$

where R is the radius of the yarn assuming a round cross-sectional shape. The average yarn curvature K_2 imposed by either the knot or the loop, again assuming a round yarn geometry, is

$$K_2 = \frac{1}{2R}$$

The ratio $\frac{K_2}{K_1}$ approaches 1 for $\theta = 45°$.)

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APPENDIX

TABLE 22

INDIVIDUAL TEST DATA FOR LOW STRAIN RATE TENSILE TESTS
(0.167%/sec)

Material	Temp (°F)	Denier at Temp	Corrected Gauge Length (inch)	Rupture Tenacity (gpd)	Rupture Elongation (%)	Initial Modulus (gpd)	Energy to Rupture, from Typical Curve (gpd)
Kevlar 29	-65	1530	10.8	22.7	3.5	637	
				23.1	3.5	623	
				21.0	3.4	585	
				24.0	3.6	621	
				23.9	3.7	611	
			Avg	22.9	3.5	615	0.40
	70	1530	10.8	21.0	3.6	514	
				19.8	3.5	499	
				21.3	3.7	508	
				21.3	3.7	504	
				20.6	3.5	508	
			Avg	20.8	3.6	507	0.35
	200	1480	10.8	19.3	3.5	447	
				18.4	3.3	448	
				19.5	3.4	465	
				18.7	3.5	447	
				18.7	3.4	428	
			Avg	18.9	3.4	447	0.29
	400	1450	10.8	14.1	2.9	388	
				13.1	2.8	395	
				14.2	3.0	366	
				13.0	2.9	363	
				14.1	3.1	347	
			Avg	13.7	2.9	372	0.19
	600	1440	10.8	7.9	2.0	368	
				7.3	1.9	376	
				8.4	2.1	342	
				7.7	1.9	361	
				8.6	2.2	354	
			Avg	8.0	2.0	360	0.08
	800	1460	10.7	2.7	0.8	381	
				2.3	0.6	386	
				1.6	0.5	361	
				2.2	0.6	378	
				2.7	0.8	356	
			Avg	2.3	0.7	372	0.01

TABLE 22 (Cont.)

INDIVIDUAL TEST DATA FOR LOW STRAIN RATE TENSILE TESTS
(0.167%/sec)

Material	Temp (°F)	Denier at Temp	Corrected Gauge Length (inch)		Rupture Tenacity (gpd)	Rupture Elongation (%)	Initial Modulus (gpd)	Energy to Rupture, from Typical Curve (gpd)
Kevlar 49	- 65	410	10.4		18.6	2.1	889	
					20.8	2.0	1051	
					17.6	2.0	913	
					17.2	1.9	937	
					18.9	2.1	937	
					18.6	2.0	945	0.19
	70	410	10.4		19.5	2.3	832	
					19.7	2.3	846	
					18.6	2.2	836	
					18.1	2.3	838	
					16.4	2.0	851	
				Avg	18.5	2.2	841	0.20
	200	395	10.4		16.2	2.0	898	
					17.7	2.1	815	
					13.6	1.6	815	
					15.9	1.8	885	
					16.1	1.8	860	
				Avg	15.9	1.9	855	0.15
	400	395	10.4		12.2	1.6	850	
					10.1	1.3	740	
					11.1	1.6	753	
					8.4	1.5	731	
					9.6	1.4	748	
				Avg	10.3	1.5	764	0.08
	600	390	10.4		5.3	0.8	671	
					4.3	0.7	652	
					6.2	1.1	635	
					7.1	1.2	635	
					6.9	1.2	671	
				Avg	6.0	1.0	653	0.03
	800	390	10.2		4.1	0.8	382	
					4.1	0.8	497	
					5.0	0.8	553	
					5.0	0.8	553	
					3.3	0.6	558	
				Avg	4.3	0.8	509	0.02

TABLE 22 (Cont.)

INDIVIDUAL TEST DATA FOR LOW STRAIN RATE TENSILE TESTS
(0.167%/sec)

Material	Temp (°F)	Denier at Temp	Corrected Gauge Length (inch)		Rupture Tenacity (gpd)	Rupture Elongation (%)	Initial Modulus (gpd)	Energy to Rupture, from Typical Curve (gpd)
PRD-49 IV	- 65	410	10.4		21.1	2.6	857	
					19.7	1.8	1076	
					21.4	2.8	774	
					23.6	3.0	819	
					21.7	2.9	819	
				Avg	21.5	2.6	869	0.23
	70	410	10.4		18.3	2.6	735	
					20.1	2.9	735	
					17.0	2.5	754	
					20.0	2.7	754	
					18.3	2.5	754	
				Avg	18.7	2.6	746	0.24
	200	395	10.4		16.5	2.4	716	
					15.5	2.4	679	
					15.3	2.3	686	
					15.0	2.3	745	
					16.8	2.7	664	
				Avg	15.8	2.4	698	0.19
	400	395	10.4		10.0	2.0	566	
					9.7	2.0	576	
					10.6	2.0	603	
					10.2	1.7	598	
					12.0	2.1	610	
				Avg	10.5	2.0	591	0.11
	600	390	10.4		6.6	1.3	544	
					6.1	1.0	610	
					7.3	1.1	666	
					7.5	1.4	666	
					7.6	1.3	666	
				Avg	7.0	1.2	630	0.04
	800	390	10.2		4.7	0.8	595	
					5.2	0.9	577	
					5.8	0.9	583	
					5.4	0.9	606	
					3.9	0.6	454	
				Avg	5.0	0.8	563	0.02

TABLE 22 (Cont.)

INDIVIDUAL TEST DATA FOR LOW STRAIN RATE TENSILE TESTS
(0.167%/sec)

Material	Temp (°F)	Denier at Temp	Corrected Gauge Length (inch)	Rupture Tenacity (gpd)	Rupture Elongation (%)	Initial Modulus (gpd)	Energy to Rupture, from Typical Curve (gpd)
PBI	-65	210	10.7	6.5	11.5	133	
				6.5	10.2	146	
				6.1	8.1	156	
				6.2	8.8	146	
				6.1	10.5	146	
			Avg	6.3	9.8	145	0.44
	70	210	10.7	5.7	14.5	126	
				5.9	15.6	126	
				5.7	15.9	126	
				6.0	17.3	126	
				5.6	16.4	124	
			Avg	5.8	15.9	126	0.61
	200	195	10.6	6.9	14.7	120	
				7.2	16.3	120	
				7.1	16.6	119	
				6.9	15.6	121	
				7.6	17.6	120	
			Avg	7.1	16.2	120	0.71
	400	190	10.6	6.0	14.9	96	
				6.1	15.0	101	
				6.2	16.5	90	
				5.9	15.5	102	
				6.0	16.3	89	
			Avg	6.0	15.6	96	0.53
	600	190	10.6	3.8	14.3	70	
				4.6	16.2	83	
				4.6	17.0	83	
				3.8	13.2	77	
				3.6	14.5	83	
			Avg	4.1	15.0	79	0.36
	800	240	7.8	0.9	3.9	33	
				0.8	3.3	35	
				0.8	4.3	29	
				0.8	4.8	27	
				0.8	3.2	32	
			Avg	0.8	3.9	31	0.02

TABLE 23

INDIVIDUAL TEST DATA FOR HIGH STRAIN RATE TENSILE TESTS (8000%/sec)

Material	Temp (°F)	Denier at Temp	Corrected Gauge Length (inch)	Rupture Tenacity (gpd)	Rupture Elongation (%)	Initial Modulus (gpd)	Energy to Rupture, from Typical Curve (gpd)
Kevlar 29	-65	1530	10.8	19.0	3.3	580	
				18.4	3.3	560	
				17.8	3.5	510	
				17.2	3.1	550	
				17.8	3.1	570	
			Avg	18.0	3.3	550	0.30
	70	1530	10.8	18.0	3.1	580	
				16.7	3.3	500	
				17.3	3.3	520	
				16.1	2.9	550	
				19.1	3.3	580	
			Avg	17.5	3.2	550	0.28
	170	1480	10.8	18.2	3.5	520	
				18.4	3.3	560	
				18.7	3.1	600	
				16.6	3.0	550	
				18.4	3.1	590	
			Avg	18.1	3.2	560	0.29
	370	1450	10.8	14.2	3.0	470	
				14.6	3.1	470	
				15.8	3.2	490	
				14.9	3.0	500	
				17.1	3.1	550	
			Avg	15.3	3.1	500	0.24
	570	1440	10.8	10.4	2.5	420	
				10.1	2.4	420	
				10.7	2.2	490	
				12.1	2.7	450	
				9.3	2.2	420	
			Avg	10.5	2.4	440	0.13
	750	1430	10.8	5.4	1.7	320	
				4.9	1.7	290	
				5.2	1.5	350	
				4.4	1.5	290	
				5.1	1.8	280	
			Avg	5.0	1.6	310	0.04

TABLE 23 (Cont.)

INDIVIDUAL TEST DATA FOR HIGH STRAIN RATE TENSILE TESTS (8000%/sec)

Material	Temp (°F)	Denier at Temp	Corrected Gauge Length (inch)	Rupture Tenacity (gpd)	Rupture Elongation (%)	Initial Modulus (gpd)	Energy to Rupture, from Typical Curve (gpd)
Kevlar 49	-65	410	10.4	14.7	2.3	640	
				14.4	1.9	760	
				14.4	1.9	760	
				15.0	2.1	710	
				14.4	2.3	630	
			Avg	14.6	2.1	700	0.15
	70	410	10.4	16.9	2.3	740	
				14.9	2.3	650	
				14.4	2.0	720	
				16.4	2.2	750	
				16.4	2.2	750	
			Avg	15.8	2.2	720	0.17
	170	395	10.4	15.1	2.2	690	
				15.6	2.1	740	
				15.9	2.2	730	
				14.4	2.1	690	
				16.7	2.1	800	
			Avg	15.5	2.1	730	0.16
	370	395	10.4	14.7	2.2	660	
				15.3	2.3	660	
				14.1	2.1	670	
				13.3	2.2	600	
				15.3	2.3	660	
			Avg	14.5	2.2	650	0.16
	570	390	10.4	13.1	1.9	690	
				14.1	2.2	640	
				15.8	2.1	750	
				9.7	1.4	690	
				14.1	2.5	570	
			Avg	13.4	2.0	670	0.13
	750	390	10.2	6.9	--------- See Text ---------		
				5.9			
				7.8			
				5.4			
				6.4			
			Avg	6.5			

TABLE 23 (Cont.)

INDIVIDUAL TEST DATA FOR HIGH STRAIN RATE TENSILE TESTS
(8000%/sec)

Material	Temp (°F)	Denier at Temp	Corrected Gauge Length (inch)		Rupture Tenacity (gpd)	Rupture Elongation (%)	Initial Modulus (gpd)	Energy to Rupture, from Typical Curve (gpd)
PRD-49 IV	-65	410	10.4		15.5	2.8	550	
					16.6	2.6	640	
					14.4	2.4	590	
					14.9	2.7	550	
					15.5	2.8	550	
				Avg	15.4	2.7	580	0.21
	70	410	10.4		18.0	2.8	650	
					16.9	2.9	590	
					16.0	2.8	580	
					16.6	2.9	580	
					16.0	2.7	600	
				Avg	16.7	2.8	600	0.23
	170	395	10.4		17.9	3.0	590	
					16.7	3.0	560	
					17.3	3.0	580	
					17.3	3.1	560	
					17.0	3.0	570	
				Avg	17.2	3.0	570	0.26
	370	395	10.4		13.3	2.5	530	
					9.9	2.1	470	
					13.3	2.5	530	
					13.3	2.5	530	
					13.6	2.5	540	
				Avg	12.7	2.4	520	0.15
	570	390	10.4		10.5	2.3	450	
					11.4	2.3	490	
					11.7	2.2	530	
					8.7	1.7	510	
					11.1	1.9	590	
				Avg	10.7	2.1	510	0.11
	750	390	10.3		5.0	1.4	360	
					6.2	1.1	560	
					6.0	1.1	550	
					6.8	1.2	570	
					7.0	1.4	500	
				Avg	6.2	1.2	510	0.04

TABLE 23 (Cont.)

INDIVIDUAL TEST DATA FOR HIGH STRAIN RATE TENSILE TESTS (8000%/sec)

Material	Temp (°F)	Denier at Temp	Corrected Gauge Length (inch)	Rupture Tenacity (gpd)	Rupture Elongation (%)	Initial Modulus (gpd)	Energy to Rupture, from Typical Curve (gpd)
PBI	-65	210	10.7	7.1	12.1	110	
				7.8	10.7	90	
				7.4	8.9	110	
				6.7	7.9	110	
				7.4	10.7	120	
			Avg	7.3	10.1	110	0.49
	70	210	10.7	6.4	12.6	110	
				6.2	13.1	110	
				6.9	14.9	110	
				6.2	12.6	110	
				5.9	11.2	110	
			Avg	6.3	12.9	110	0.55
	170	195	10.6	6.8	13.2	110	
				7.4	13.2	110	
				6.9	12.2	120	
				7.3	12.7	110	
				7.2	14.0	110	
			Avg	7.1	13.1	110	0.62
	370	190	10.6	5.1	8.2	100	
				5.6	9.9	100	
				5.6	8.0	110	
				5.6	7.6	110	
				6.4	10.4	110	
			Avg	5.7	8.8	106	0.31
	570	190	10.6	4.2	5.7	100	
				4.6	8.5	110	
				4.2	11.5	100	
				6.1	16.5	100	
				5.9	15.5	90	
			Avg	5.0	11.5	100	0.41
	750	240	8.5	1.9	2.9	89	
				1.3	2.6	50	
				1.7	3.5	54	
				1.7	2.9	52	
				1.4	2.9	73	
			Avg	1.6	3.0	64	0.03

TABLE 24

TENSILE PROPERTIES OF KEVLAR FIBERS

Material	Gauge Length (inch)	Initial Modulus (gpd)		Maximum Modulus (gpd)		Rupture Elongation (%)		Rupture Tenacity (gpd)	
Kevlar 29	1.0	----		----		4.1	4.3	27.6	27.4
						4.0	4.1	24.0	27.0
						4.9	4.6	27.0	28.0
						4.3	4.1	27.3	24.5
						4.2	4.7	27.0	27.5
						4.8	4.3	28.4	25.2
						4.8		29.0	
	Avg					4.4		26.9	
	CV (%)					7.2		5.5	
	Group→	I	II	I	II	I	II	I	II
	3.0	631	609	751	662	3.5	4.1	25.2	26.9
		656	631	751	734	3.9	4.0	28.0	28.1
		541	497	720	682	4.0	4.4	26.0	25.5
		609	497	689	662	3.7	4.3	25.7	26.4
		631	476	743	662	3.7	4.5	26.2	26.4
		568	463	711	662	3.9	4.5	25.8	27.0
		631	497	768	720	3.7	4.6	26.7	28.9
		558	466	689	682	4.1	4.3	27.1	24.9
		588	508	704	643	3.5	4.4	23.6	26.8
		598	558	704	650	3.9	4.1	26.7	26.7
		631	541	751	720	---	4.5	---	29.1
		598	490	720	682	3.9	4.4	27.0	26.8
		603	508	727	650	3.8	4.6	26.0	27.8
		631	536	727	719	3.9	4.3	27.6	27.7
		609		711		3.9		26.3	
	Avg	606	520	724	681	3.8	4.4	26.3	27.1
	CV (%)	5.2	9.7	3.3	4.5	4.6	4.3	4.1	4.3
	5.0	571	483	786	784	3.9	4.0	26.8	24.3
		522	524	765	812	4.1	4.3	26.3	28.6
		555	517	770	749	4.0	3.8	26.6	24.3
		619	557	808	739	3.6	4.1	25.0	25.4
		474	540	711	768	4.0	4.1	24.8	27.0
		501	617	721	788	4.2	3.9	26.1	26.4
		468	520	695	665	3.9	4.4	22.6	28.3
		560	552	749	751	3.8	4.0	25.3	25.9
		420	581	657	725	4.0	3.6	21.9	23.6
		490	651	759	808	3.8	3.8	24.1	27.8
		506	488	754	786	3.9	3.7	24.7	23.7
		539	555	765	683	3.8	4.1	24.6	27.0
			650		806		3.8		27.7
			474		717		4.0		24.1
			590		759		3.9		26.2
			580		782		3.8		26.2
			642		784		3.8		27.0
			642		810		3.7		26.6
	Avg	522	570	743	762	3.8	3.9	24.9	26.1
	CV (%)	10.2	10.2	5.6	5.6	11.1	5.1	13.0	6.0

TABLE 24 (Cont.)

TENSILE PROPERTIES OF KEVLAR FIBERS

Material	Gauge Length (inches)		Initial Modulus (gpd)	Maximum Modulus (gpd)	Rupture Elongation (%)	Rupture Tenacity (gpd)
Kevlar 49	1.0				2.6	25.5
					2.3	21.3
					2.9	26.6
					2.7	24.2
					3.1	30.1
					2.1	20.6
					2.8	29.3
					2.9	26.8
					2.8	25.1
					2.7	26.7
					3.1	32.0
					2.1	21.1
					2.8	26.0
					2.7	26.2
					2.7	27.4
					3.1	31.9
					2.5	24.6
		Avg			2.7	26.2
		CV (%)			11.4	12.9
	5.0		986	1093	2.3	23.5
			991	1072	2.6	25.7
			1012	1099	2.1	22.5
			1045	1126	2.3	24.8
			948	1072	2.0	19.0
			980	1093	2.2	22.8
			910	1050	1.9	18.7
			996	1099	2.5	26.3
			975	1039	2.3	22.6
			996	1099	2.8	28.2
			1018	1110	1.9	20.0
			953	1061	2.5	24.2
			932	1066	2.4	23.4
			1013	1099	2.6	26.8
			---	1061	2.5	25.3
			1012	1120	2.3	24.0
			1061	1136	2.5	26.4
		Avg	989	1088	2.3	23.8
		CV (%)	4.0	2.5	10.9	11.3

TABLE 25

TENSILE PROPERTIES OF TWISTED KEVLAR YARNS
(20 inch specimen length)

Material	Yarn Twist (tpi)	Denier	Initial Modulus (gpd)	Rupture Elongation (%)	Rupture Tenacity (gpd)	Strength Change (%) *	Strength Change (%) **
Kevlar 29	0	1054	586	3.2	21.2		
		1055	576	3.3	21.2		
		1069	589	3.2	21.2		
		1054	591	3.2	21.2		
		1052	592	3.2	20.8		
Avg		1057	587	3.2	21.1	-18	---
	3.5	1079	535	3.7	24.1		
	3.4	1071	540	3.7	24.1		
	3.8	1067	528	3.9	24.5		
	3.6		569	3.7	24.5		
	3.8		522	3.9	24.5		
Avg	3.6	1072	539	3.8	24.3	- 5	+15
	8.0	1115	407	4.0	20.3		
	8.0	1125	376	4.0	19.1		
	8.2	1110	412	4.2	21.5		
	7.8		376	3.9	17.9		
	7.9		363	4.1	19.6		
Avg	8.0	1117	387	4.0	19.7	-23	- 7
	14.1	1184	131	5.7	11.7		
	14.1	1187	130	5.4	11.0		
	13.8	1183	149	5.0	11.9		
	14.2		136	5.3	10.8		
	13.6		201	4.7	14.4		
Avg	14.0	1185	149	5.2	11.9	-54	-44

*Based on individual fiber strength at a 5.0 inch gauge length.
**Based on the strength of the untwisted yarn.

TABLE 25 (Cont.)

TENSILE PROPERTIES OF TWISTED KEVLAR YARNS
(20 inch specimen length)

Material		Yarn Twist (tpi)	Denier	Initial Modulus (gpd)	Rupture Elongation (%)	Rupture Tenacity (gpd)	Strength Change (%) *	**
Kevlar 49		0	405	936	1.9	18.7		
			404	919	2.0	19.7		
			405	945	2.0	18.8		
			406	949	2.0	19.0		
			405	939	1.9	18.5		
	Avg		405	938	2.0	18.9	-21	---
		6.3	406	813	2.3	21.9		
		6.5	405	847	2.3	21.6		
		6.6	408	852	2.1	19.8		
		6.7		842	2.3	21.0		
		6.5		786	2.0	17.0		
	Avg	6.5	406	828	2.2	20.3	-15	+ 7
		13.6	433	338	2.5	10.8		
		13.4	431	519	2.4	19.0		
		14.1	433	333	2.4	13.8		
		14.2		394	2.7	16.7		
		13.7		343	2.7	12.5		
				326	2.7	15.4		
				331	2.7	14.4		
				442	2.3	14.4		
				350	2.7	16.1		
	Avg	13.8	432	375	2.6	14.8	-38	-22
		22.3	458	176	3.1	8.6		
		22.5	458	146	3.6	8.7		
		22.3	459	146	3.8	9.2		
		22.4		139	4.5	9.3		
		22.2		157	4.4	10.1		
				152	4.3	9.7		
				137	4.3	10.9		
				161	4.4	11.1		
				167	4.4	10.8		
	Avg	22.3	458	154	4.1	9.8	-59	-48

*Based on individual fiber strength at a 5.0 inch gauge length.
**Based on the strength of the untwisted yarn.

TABLE 26

TENSILE PROPERTIES OF FIBERS REMOVED FROM TWISTED KEVLAR YARNS
(5.0 inch gauge length)

Material	Yarn Twist (tpi)	Initial Modulus (gpd)		Rupture Elongation (%)		Rupture Tenacity (gpd)		Strength Change (%)
Kevlar 29	0	546		3.9		25.6		---
	3.6	485	478	4.3	3.4	27.4	20.2	
		515	520	3.9	3.2	23.1	18.9	
		613	613	3.9	3.2	26.7	22.4	
		648	613	3.7	3.9	25.9	27.6	
		539	530	3.7	3.8	24.3	22.5	
	Avg	555		3.7		23.9		-7
	CV(%)	10.9		9.4		12.6		
	8.0	509	482	3.1	4.0	19.0	24.4	
		453	474	3.9	4.2	22.3	25.7	
		585	513	3.8	4.3	25.1	25.8	
		533	546	3.6	2.7	15.8	16.2	
		561	488	3.6	3.7	22.4	24.7	
	Avg	514		3.7		22.1		-14
	CV(%)	8.1		13.2		17.3		
	14.0	505	519	3.3	3.4	19.9	20.6	
		465	530	3.4	3.0	18.9	16.1	
		433	572	2.8	3.4	13.5	22.3	
		565	573	3.4	3.0	21.9	19.3	
		543		3.1		18.9		
	Avg	523		3.2		19.2		-25
	CV(%)	9.3		7.2		23.8		

TABLE 26 (Cont.)

TENSILE PROPERTIES OF FIBERS REMOVED FROM TWISTED KEVLAR YARNS
(5.0 inch gauge length)

Material	Yarn Twist (tpi)	Initial Modulus (gpd)		Rupture Elongation (%)		Rupture Tenacity (gpd)		Strength Change (%)
Kevlar 49	0	989		2.3		23.8		---
	6.5	976	991	2.2	2.3	22.4	23.9	
		933	962	2.0	2.2	19.7	22.6	
		1021	925	2.5	2.1	27.2	20.0	
		946	938	2.2	2.3	21.4	22.8	
		1002	894	2.2	2.4	23.4	23.1	
	Avg	959		2.2		22.6		-5
	CV (%)	4.1		6.4		9.4		
	13.8	898	954	2.3	2.0	21.9	19.0	
		936	906	2.0	2.0	20.3	15.6	
		993	954	1.4	1.5	14.1	19.5	
		931	894	1.9	2.1	18.7	19.5	
		889	954	1.4	1.9	21.0		
	Avg	931		1.9		18.8		-21
	CV (%)	3.6		16.8		13.3		
	22.3	853	954	1.1	1.6	18.0	14.5	
		903	936	1.9	1.5	15.8	20.2	
		918	982	1.7	2.0	16.2	15.5	
		876	911	1.7	1.6	14.1	17.2	
		868	928	1.6	1.8	15.5		
	Avg	913		1.7		16.3		-32
	CV (%)	4.4		14.9		11.6		

TABLE 27

TENSILE PROPERTIES OF TWISTED KEVLAR 29 FIBERS
(5.0 inch gauge length)

Yarn Twist (tpi)		Initial Modulus (gpd)	Rupture Elongation (%)	Rupture Tenacity (gpd)
0	Avg	546	3.9	25.6
8		479	4.4	27.4
		---	3.3	27.0
		537	3.8	24.7
		609	3.6	23.6
		582	4.0	26.3
	Avg	552	3.8	25.8
14		613	3.5	24.9
		550	4.0	26.7
		614	3.7	26.3
		555	3.7	24.3
		499	4.1	26.8
	Avg	566	3.8	25.8

TABLE 28

TENSILE PROPERTIES OF PREVIOUSLY BENT KEVLAR 49 FIBERS
(1.0 inch gauge length)

Mandrel Diameter (inches)		Initial Modulus (gpd)		Rupture Elongation (%)		Rupture Tenacity (gpd)		Strength Change (%)
0		989		2.7		26.2		---
0.33		1039	954	2.7	1.9	27.7	20.9	
		840	923	2.4	1.7	29.1	27.7	
(ε = 0.14%)		1030	1005	2.8	2.9	23.0	18.9	
		1014	976	2.8	2.6	19.6	15.5	
		1024	954	2.3	3.2	29.7	25.7	
		960		2.0		30.4		
	Avg	974		2.5		24.4		-7
	CV(%)	6.0		18.8		21		
0.086		1072	971	2.4	2.8	26.4	22.3	
		1063	928	2.1	2.9	28.4	22.3	
(ε = 0.54%)		1036	949	2.7	2.6	21.6	24.3	
		938	1097	2.3	3.1	26.4	26.4	
		944	968	2.2	1.9	25.7	27.7	
		920	1002	2.7	2.3	27.0	25.0	
		993	999	2.8	2.6	28.4	19.6	
		1002		2.5		23.0		
	Avg	992		2.5		24.9		-5
	CV(%)	5.5		12.9		11		
0.040		971	965	2.4	2.5	25.0	22.3	
		944	1052	2.6	2.7	25.7	25.7	
(ε = 1.16%)		894	971	2.1	2.3	24.3	22.3	
		991	976	2.5	2.8	25.0	24.3	
		1059	894	2.5	2.8	27.7	23.6	
		844	965	2.8	2.2	27.7	20.9	
	Avg	960		2.5		24.0		-8
	CV(%)	6.4		9.4		11		

TABLE 29

TENSILE PROPERTIES OF TRANSVERSELY COMPRESSED FIBERS
(1.0 inch gauge length)

Material	Transverse Load (lbs/inch)		Rupture Elongation (%)		Rupture Tenacity (gpd)	
Kevlar 29	0		4.0	3.8	22.3	23.0
			3.5	3.8	23.6	21.6
			4.3	4.5	18.9	25.0
			3.9	4.8	27.0	20.3
			3.3	4.5	20.3	23.6
			3.7	3.8	25.5	25.6
			4.2	4.2	25.6	22.6
		Avg	4.0		23.2	
		CV(%)	10.4		10.3	
	18		4.2	4.3	18.9	22.0
			2.8	4.5	13.9	21.6
			3.2	4.5	14.4	24.0
			3.5	4.7	16.2	22.5
			4.1	4.8	20.5	27.0
			4.2	5.1	22.6	22.3
				5.0		24.4
		Avg	4.2		20.7	
		CV(%)	16.3		18.9	
	110		4.5	3.7	21.0	19.6
			4.8	2.5	20.6	18.2
			4.6	2.3	21.0	10.1
			3.6	2.8	16.9	9.4
			3.6	4.6	18.8	13.5
			4.1	5.0	19.1	21.6
			4.6	3.7	23.3	18.2
		Avg	3.9		18.0	
		CV(%)	22.3		23.3	

TABLE 29 (Cont.)

TENSILE PROPERTIES OF TRANSVERSELY COMPRESSED FIBERS
(1.0 inch gauge length)

Material	Transverse Load (lbs/inch)		Rupture Elongation (%)		Rupture Tenacity (gpd)	
Kevlar 49	0		2.8	2.6	30.4	26.4
			3.0	2.5	30.4	23.0
			2.7	2.8	29.9	29.0
			2.7	2.7	28.8	29.0
			3.0	2.7	29.4	29.0
			2.8	2.5	27.0	24.3
				2.8		25.3
		Avg	2.7		27.8	
		CV(%)	5.7		8.6	
	18		2.6	2.7	24.6	26.0
			2.5	1.8	24.3	16.9
			3.0	2.6	27.0	30.0
			2.7	2.6	26.4	25.7
			3.1	1.5	28.4	26.7
			2.9	1.1	16.5	22.6
			1.8	2.6	23.6	18.9
			3.0	2.8	10.1	27.0
			3.0	2.8	27.0	25.0
		Avg	2.5		23.7	
		CV(%)	22.8		21.1	
	110		3.1	2.5	23.0	18.3
			2.6	3.0	20.4	19.3
			2.5	2.8	21.3	22.3
			2.7	2.4	21.1	20.6
			3.0	2.4	20.3	20.6
				2.4		21.6
		Avg	2.7		20.8	
		CV(%)	9.6		6.3	

TABLE 29 (Cont.)

TENSILE PROPERTIES OF TRANSVERSELY COMPRESSED FIBERS
(1.0 inch gauge length)

Material	Transverse Load (lbs/inch)		Rupture Elongation (%)			Rupture Tenacity (gpd)		
Nylon	0		31		23	6.45		6.35
			35		30	6.75		5.85
			32.5		23	6.75		6.35
			26		33	6.54		6.83
		Avg		29.2			6.48	
		CV(%)		15.9			4.89	
	18		20		26	6.02		6.36
			22		19	6.25		6.36
			25		21	6.25		5.87
			18		24	6.36		5.87
			18		21	5.87		5.87
					20			5.90
		Avg		21			6.09	
		CV(%)		13.7			3.69	
	110		25.5		22.0	6.20		5.60
			18.0		19.5	5.13		5.71
			24.2		21.7	5.95		5.40
			19.5		21.0	5.40		5.61
			19.0		20.0	4.97		5.51
					25.1			5.95
		Avg		21.4			5.59	
		CV(%)		11.9			6.51	

TABLE 30

LOOP STRENGTH OF TWISTED KEVLAR YARNS

Material	Yarn Twist (tpi)		Loop Strength (gpd)		Loop Efficiency (%)
Kevlar 29	0		13.4		
			14.0		
			13.6		
			13.4		
			13.6		
		Avg	13.6		64
	3.6		13.2	12.7	
			11.0	13.2	
			12.5	10.9	
			14.3	12.9	
			12.2	12.6	
		Avg	12.6		52
	8.0		12.4	10.9	
			13.1	12.2	
			11.1	10.5	
			13.4	10.6	
			13.2	11.8	
		Avg	11.9		60
	14.0		8.4	8.2	
			9.1	9.1	
			8.3	8.0	
			8.3	8.4	
			7.9	9.2	
		Avg	8.5		71

TABLE 30 (Cont.)

LOOP STRENGTH OF TWISTED KEVLAR YARNS

Material	Yarn Twist (tpi)		Loop Strength (gpd)		Loop Efficiency (%)
Kevlar 49	0		10.0		
			11.6		
			10.5		
			10.3		
			11.0		
		Avg	10.7		57
	6.5		7.4	7.7	
			6.7	8.4	
			6.8	7.9	
			9.2	7.7	
			8.7	7.8	
		Avg	7.8		38
	13.8		7.8	8.0	
			7.8	6.6	
			6.5	7.5	
			6.7	8.0	
			6.0	9.0	
		Avg	7.4		50
	22.3		8.3	8.2	
			7.0	5.6	
			8.0	7.7	
			8.0	5.4	
			7.1	3.9	
		Avg	6.9		70

TABLE 31

KNOT STRENGTH OF TWISTED KEVLAR YARNS

Material	Yarn Twist (tpi)		Knot Strength (gpd)	Knot Efficiency (%)
Kevlar 29	0		8.5	
			9.9	
			8.4	
			7.7	
			8.2	
		Avg	8.5	40
	3.6		7.1	
			7.1	
			7.2	
			8.4	
			8.1	
		Avg	7.6	31
	8.0		9.1	
			10.6	
			9.3	
			9.1	
			9.8	
		Avg	9.6	49
	14.0		7.2	
			7.8	
			6.5	
			8.3	
			8.2	
		Avg	7.6	64

TABLE 31 (Cont.)

KNOT STRENGTH OF TWISTED KEVLAR YARNS

Material	Yarn Twist (tpi)		Knot Strength (gpd)	Knot Efficiency (%)
Kevlar 49	0		8.1	
			7.3	
			6.3	
			7.2	
			8.3	
		Avg	7.4	39
	6.5		7.1	
			6.1	
			9.3	
			8.4	
			7.7	
		Avg	7.7	38
	13.8		8.6	
			7.7	
			8.7	
			8.3	
			7.6	
		Avg	8.2	55
	22.3		5.7	
			7.8	
			4.1	
			6.0	
			7.9	
		Avg	63	64

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